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**MICROBUBBLES AND CAVITATION**

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## 1. Introduction

The present report arose from a joint effort of the California Institute of Technology, The Catholic University of America and the David Taylor Naval Ship Research and Development Center. The initial purpose was to document by both light-scattering and holographic techniques the distribution of microbubbles in laboratory cavitation test facilities (under different conditions of cavitation testing), to compare these two different techniques where feasible and then, as the last stage, to make similar observations of nuclei in natural - or oceanic waters. It has been apparent to many workers in the field of cavitation inception that there has not yet been adequate correlation of laboratory and field conditions for cavitation testing - particularly for cavitation inception testing. Thus the proposed work offered the first real opportunity to explore this important connection. Caltech's role in this work was to design and build a holographic system that would be suitable for use either in the laboratory or the field. In the first case we anticipated making laboratory nuclei observations in the Institute's Low Turbulence Water Tunnel (LTWT) jointly with the light-scattering device designed by Professor S. C. Ling of C.U.A. and developed further by Mr. S. Gowing of DTNSRDC. For the latter case, the field work, it was proposed to install the holographic system in a submersible tank to permit holographic recordings of a suitable test volume of fluid. As an initial goal a depth of 100 feet was selected for the maximum depth of operation.

After initiation of the work the last stage or field task was deleted as a part of the project. And in addition a serious delay in our part was occasioned by illness. Nevertheless, the basic objectives of the project have been accomplished. Briefly, these were to provide the LTWT with air content



(hence nuclei) control, to construct a submersible apparatus that would contain a holocamera, and to use the holocamera in a laboratory test with the light-scattering instrument developed by C.U.A. We have not had sufficient time nor resources to test the underwater holocamera in the field, however.

In the remainder of the report the principles of the holographic system adopted are described, the optical cavity and the components thereof, the submersible tank and associated cabling, various electronic and control circuits, optical reconstruction systems, sample holograms and reconstructions are all discussed. The joint light-scattering work is the subject of a separate report under the present contract [Ref.10 of the present report].

## 2. Holographic Photography.

Out of the different techniques of measuring the population of microscopic particulates in a moving fluid only one, namely holography, enables direct observation of these particulates and thus, identify their nature, shape and size. This technique has already been applied extensively in different investigations such as the study of fog and aerosol particles by Thompson and Ward (1966), the detection of coal and fuel spray in combustion chambers by Trolinger (1975, 1978), the identification of microplankton in the ocean by Beers et al (1973), and the study of cavitation nuclei by Feldberg and Shlemenson (1973), Peterson et al (1975), Gates and Acosta (1978), Katz (1981), and Ooi (1981).

The physical principles of holography can be explained by comparing this technique to conventional photography. When a photograph is recorded we usually focus a certain cross-section of an object onto a film plane and record

the intensity of light scattered from this object. The image is usually sharp and clear in the neighborhood of the focused plane and loses its resolution outside of this narrow region of focus. The photograph does not contain any information about the relative location of different objects in space and their distance from the film plane. A hologram, however, is a record of interference between two light sources, a reference beam and the light scattered from the objects in an illuminated sample volume. As a result, this hologram contains information about the phase difference between these waves and thus about the exact location of the different objects in space. Illumination of the hologram with another coherent light beam results in the reconstruction of a three dimensional image of the original sample volume. The observations and measurements can be then made in this reconstructed image at almost any desired magnification.

Being a record of interference between two waves, the quality of the hologram depends on the ability of these waves to interfere, that is on the coherence of both the holocamera light source and the beams which result from the manipulation of this light. The need for a coherent source requires the use of a laser that can generate polarized, monochromatic and single-mode beams. Since the existing lasers have limited coherence properties (limited coherence length) they impose a limitation on our ability to produce clear interference patterns. As a result, a careful design of the optical system is needed for maintaining and bringing the available partially coherent light to maximum use. In addition, since we want to identify moving microscopic objects, some of them as small as 10 microns in diameter, exposure time of the sample volume must be short enough to prevent blurring of the image. If, for example, the velocity of a particle is 10 m/sec it takes 1 microsecond for

this particle to move 10 microns. Thus, in order to obtain a clear image of the microscopic object, the exposure time must be of the order of 10 nanoseconds. This requirement limits our choice of light source to high energy pulsed laser, and in this category the ruby laser is the most convenient at the present time. Thus, we have opted for a ruby laser holographic camera whose detailed description is provided in the sections that follow.

Two techniques of recording holograms, namely classical double-beam, off-axis holography and in-line lensless Fraunhofer holography are optional in the present system. The physical principles of these techniques are described briefly herein and the reader can refer to Collier et al (1971) for detailed information and mathematical analysis. As noted before, the formation of a holographic image requires two stages, the first one being the recording of a hologram in the test facility and the second being the illumination of this hologram by another laser beam to form a three dimensional image of the original volume. Classical, off-axis holography requires two beams that originate from the same source. The first beam, which is usually referred to as the subject wave, illuminates the sample volume, and the second beam is the carefully-controlled reference wave that illuminates the recording film directly. The hologram then becomes a record of interference between the light scattered from the objects in the sample volume and the reference wave. Figure 1a is a line diagram of the present holographic camera in the off-axis, double-beam configuration. The second technique, in-line holography, is simpler but is also limited to holograms recorded in the "far field" of small objects. Instead of splitting the laser beam to two waves this method requires only one beam which illuminates the sample volume. Part of this wave



is diffracted by the objects in the illuminated region and interferes with the remaining undisturbed part of this beam. The resulting interference pattern is then recorded on a high resolution film that is located on the other side of the test volume. A schematic illustration of the holocamera in the in-line configuration is presented in Fig.1b. This system has already been applied to the study of microbubbles in a water tunnel by Katz (1981), Ooi (1981) and Katz et al (1982). The main advantage of this method is its simplicity; however, this technique is more limited than the complex off-axis holocamera. The main differences are discussed in the sections that follows.

After being recorded, the holographic film is developed and then mounted on the reconstruction system. There (as shown in Fig.9a and b for the off-axis and the in-line techniques, respectively), the hologram is illuminated by a collimated, spatially filtered and expanded beam of a He-Ne laser. As a result, we form a three dimensional image of the original sample volume. Actually, at least two images are created, a real image and a virtual one and their relative location depends on the recording technique. In the in-line configuration, for example, the two images are located symmetrically on either side of the hologram plane, whereas this symmetry does not exist when the off-axis technique is applied. Further details about the present reconstruction system and examples of a reconstructed hologram are presented in Section 6.

### 3. Description of the Holocamera

Both versions of the holocamera, that is the in-line and the off-axis configurations, are shown in Figs. 1a,b respectively. The double-beam version is shown inside the submersible tank. The optical cavity of the in-line version is shown removed from the tank and mounted on an optical bench near the

test facility, ((LTWT), see Katz et al (1982) for details). As will be described later, only minor changes are required for transferring the system from one version to the other and the proper adjustments require very little time.

Most of the optical components are mounted on a 30 inch long, 20 inch wide and 0.5 inch thick aluminum optical table whose upper surface is located 4.125 inch below the centerline of the submersible tank. This plate is connected to a drawer mechanism through four rubber shock absorbers and can be pulled out of the tank for adjustment and alignment. A general view of the submersible tank with the optical drawer inside is shown in Fig.2 whereas Fig.3 displays the system with the drawer pulled out. The electrical cables that provide power to different components on this table are either retractable or long enough so that the system can be operated in any drawer position. This table can also be removed from the tank and mounted as a unit near any test facility such as the water tunnel just mentioned. The optical components are connected to both sides of the aluminum plate, the alignment He-Ne laser and part of the water cooling system (pump, pipes and valves) are mounted on the bottom in order to save space. The rest of the components, including the ruby laser cavity, autocollimator, beam splitters, PIN diode, mirrors, objectives, spatial filter, collimating lens, shutter, camera, and one of the relay lenses are mounted on top of the optical table. A close-up photograph of this table and the optical components mounted on it is presented in Fig.4. Part of the optical system, such as the subject beam collimating lens, mirrors, windows and one of the relay lenses are mounted inside the pipe that leads to and from the test section of the tank. This pipe and test section can be readily observed in Figs.2 and 3. Figure 2 displays also the control

rack that carries most of the electronic control system, all of the high voltage power supply units, and the main power capacitors. Cables from this control rack lead to the remainder of the electronic control system that is mounted inside the tank. The description and sketches of these electronic control and power systems are provided in Section 5 and in Appendix II.

3.1 The Ruby Laser Cavity. The light source of the holocamera, that is the pulsed laser cavity, is included in the sketch shown in Figs.1a,b. The ruby wavelength is 0.6943 micrometers and the duration of each light pulse is between 20 to 50 nanoseconds. Two flat mirrors located sixteen inches apart create the optical cavity. The back mirror has a dielectric coating with a reflectivity of almost 100 percent whereas the front (output) mirror is a sapphire etalon (about 60 percent reflectivity) which plays an important role in longitudinal mode control. The ruby rod is three inches long and 1/4 inch diameter with anti-reflection coated faces. The rod is pumped by a helical xenon flashlamp surrounding the ruby. Both the ruby and flashlamp are contained inside a sealed stainless steel housing which is shown in Fig.5. The lamp is surrounded by a polished aluminum reflector. The interior of the laser housing is cooled with dionized, filtered water which is recirculated at the rate of about 2gpm by an on-board pulse pump. This water is injected from six orifices (each has a diameter of 0.125 inch) into the region between the ruby rod and the flashlamp in order to insure efficient cooling. The recirculating pump is attached to the bottom of the optical table through a thick vibration isolator and the water is stored inside a rubber bag on the bottom of the submersible tank. The ruby rod is held by two rubber O-rings, located very close to the ends of the ruby in order to expose most of its length to the flashlamp. The ruby rod can be rotated on its axis for align-



ment purposes without changing the positioning of the flashlamp.

The main flashlamp energy, about 1500 joules, is stored in large capacitors at 4500 volts. This energy is discharged through the lamp when a 20,000 volt pulse supplied by a series injection trigger transformer ionizes the xenon in the tube and initiates the discharge. The duration of each flash, about 1.5 millisecond, and the amount of energy provided are sufficient for generating a large number of laser pulses. Only one or two controlled pulses are needed. For this purpose the system is "Q-switched" with a  $\text{KD}^*\text{P}$  cylindrical ring electrode Pockels cell and two crossed glan calcite polarizers located on either side of the  $\text{KD}^*\text{P}$  crystal. This device prevents light oscillations in the cavity when the Pockels cell electrode is not energized. A pulse of about 4000 volts provided to the  $\text{KD}^*\text{P}$  crystal will cause a half wavelength retardation of the circularly polarized light passing through it and as a result, the polarization of the transmitted passing beam is rotated by 90 degrees. Thus, the beam is enabled to pass through the crossed polarizers after reflection and the cavity is then opened to permit light oscillations. Only one polarizer is essential to the Q-switching of the cavity since the light emitted by the ruby is already polarized: successful operation has been achieved with either one or two polarizers in place. The present system can generate two laser pulses by providing two high voltage pulses to the  $\text{KD}^*\text{P}$  crystal. The time difference between these pulses can be controlled very accurately from a minimum of less than 50 microseconds up to one half millisecond. A single laser pulse can be generated by delaying the second high voltage pulse beyond the period of the flashlamp operation.

The remaining components in the optical cavity are two iris apertures. Their main purpose is to reduce the diameter of the laser beam to about two

millimeters in order to prevent generating multiple transverse modes and insure generation of the  $TEM_{00}$  mode.

The intensity of the ruby laser light emergent from the cavity is too high for the film so it is attenuated with a neutral density filter which transmits about 10 percent of the light. Part of the remaining beam (about 4 percent) is directed by a beam splitter towards a PIN diode and the rest is split again into the subject and the reference waves. The PIN diode output can be observed directly on the oscilloscope mounted on the control rack. The remainder of the optical setup depends on the holographic technique and the details are discussed in the sections that follow.

3.2 Alignment. Two devices, namely the autocollimator and the small 1/2 milliwatt He-Ne laser are the alignment means of the holocamera. The autocollimator is used only for aligning the components of the optical cavity and the small laser is used mainly for positioning the mirrors, beam splitter, lenses and spatial filter in the proper angle and location. All the optical components are mounted on adjustable mounts for alignment purposes. Some components, such as the pinhole holder and the laser cavity optics, require precision adjustable mounts since the performance of the ruby laser is very sensitive to their alignment.

3.3 The Off-Axis Holocamera. Several features of the off-axis, double-beam holographic camera make this system superior to the simpler in-line technique. The first advantage is related to the difference in reconstruction procedures. Since the axis of the holographic image does not coincide with the axis of the He-Ne reconstruction laser, the television camera is not exposed to direct illumination by this main beam. As a result, the noise associated with the

reconstruction light source is filtered out. Secondly, since the reference beam is separated from the subject wave it can be maintained in an almost perfect form, undisturbed by window imperfections, objects in the sample volume and the imaging lenses. Thirdly, the off-axis technique is not limited to holograms recorded in the "far field" of small objects, thus eliminating any requirement concerning either the size or the location of these objects. Fourthly, the in-line hologram of a sample volume with a large object (such as a submerged body) contains a transparent section. As a result, part of the illuminating <sup>RECONSTRUCTION</sup> He-Ne beam transmits undisturbed through the holographic film, illuminates the TV camera, and creates large intensity gradients in the neighborhood of this large object. This undisturbed beam makes the detection of small particles a very difficult task. This problem does not exist when the off-axis technique is applied since the reference beam is undisturbed and the angle of observation prevents direct illumination of the camera. Finally, we can add a diffuser to the subject wave and thus provide uniform illumination of the sample volume. However, as shown in Fig.1a,b, the off-axis system is more complex, contains more components and requires careful design in order to obtain a clear undistorted image of small objects. Some of these requirements are listed as follows: First, the optical path length of the two beams, the subject and the reference waves, must be identical due to the limited coherence of the ruby laser. This problem does not exist in the in-line system since there is no separation between the two beams. Secondly, the ratio between the intensity of the reference wave and the subject wave has to be considered carefully in order to find the right compromise between the need for high diffraction efficiency (the maximum efficiency of unity occurs when the two beams have the same intensity) on one hand, and prevent nonlinear effects on the other. These nonlinearities occur when the emulsion on the



holographic film is under or over exposed, and thus may happen when the interference fringes have a large contrast due to a high diffraction efficiency. The commonly suggested ratio (see Trolinger (1979), for example) is 10:1, the reference beam being the larger one. Thirdly, the angle between the two beams must be kept as small as possible in order to increase the distance between the fringes on the hologram, thus avoiding problems associated with the resolution limitations of the film. Fourthly, in order to eliminate the effect of transverse variations in the characteristics of the laser beam the sections of the subject and reference waves that originate from the same point must also reach the film plane at identical locations and thus interfere with each other. Finally, in order to increase the image quality the sample volume must be located as close as possible to the film plane. In the present system, this requirement is achieved by adding a pair of relay lenses to the path of the subject beam that bring the image of the sample volume closer to the film plane. These lenses must have a high resolution in order to preserve the image of the microscopic nuclei.

All the requirements mentioned above have been brought into consideration in the design of the present holocamera. The two beams have almost identical optical paths (the total difference is less than 1/16 of an inch) and the intensity of each beam can be adjusted with neutral density filters. The mirrors in the path of the reference wave have a flatness of  $\lambda/10$  ( $\lambda$  being the wavelength of blue light, approximately 0.5 microns) and the reflecting surfaces are made of dielectric coating with a reflectivity of more than 99 percent. This high reflectivity is required to reduce the amount of absorption to a minimum in order to prevent the possibility of damage to the mirror. This reference beam is focused by a microscope objective and spatially

filtered with a ten micron pinhole in order to eliminate any traces of imperfections in the optical components upstream. Both collimating lenses are two-element achromats, corrected to reduce spherical aberrations, and are anti-reflection coated. The number of mirrors in the path of the reference beam also satisfies the requirement that the interfering sections of the two waves originate from the same point on the beam splitter. All the optical components are mounted on precision adjustable mounts, especially the pinhole and the components of the laser cavity. The former required a new design as is described in Appendix IV. The beam splitters also have high quality surfaces with flatness of  $\lambda/10$  and their thickness is sufficiently large so that ghost images originating from multiple reflections are separated from the main beam and thereby cut off by the pinhole. The subject beam is also expanded by a microscope objective and collimated with an achromatic lens. The large mirrors have a metallic coating and their flatness is  $\lambda/4$ . Since the role of this beam is to illuminate the sample volume the quality requirements are lower, thus avoiding the need for a spatial filter. The windows of the holocamera are made of precision optical flats (flatness of  $\lambda/20$  on one side and  $\lambda/10$  on the other) in order to prevent any distortion of the beam (both in the in-line and off-axis configuration). These windows, however, are not coated since they are exposed to the water and require frequent cleaning of salt, algae, etc. Special consideration has been given to the imaging relay lenses since they must have the capability of transmitting a clear image of particles smaller than 10 microns. Due to size constraints of the submersible tank we have opted for multi-element diffraction limited lenses with a resolution of 500 lines per mm. These lenses are positioned  $2f$  from each other ( $f$  being their focal length, 175mm) and thus, they transfer the image of the plane located at a distance  $f$  from the first lens onto the film plane with a

magnification of 1. Two other optional components can be added to the path of the subject beam, the first component being a diffuser that scatters the beam for uniform illumination of the sample volume, and the second component being an interference filter with a transmission bandwidth of 10 nanometers around the ruby laser wavelength. This filter, when placed before the relay lenses allows the operation of the holocamera during bright daylight.

The 30° angle between the reference and the subject beam is the minimum possible due to several design constraints. The film drive and the shutter are facing the bisector of this angle, and both of them are connected to the control system of the holocamera. The recording film is a 70mm Agfa-Gevaert 10E75 holography film which has a resolution of 2800 lines per mm and sensitivity of 1-3 microjoules per cm<sup>2</sup>. The automatic film drive can carry a 100 foot roll of film which is sufficient for recording 300 holograms. After each set of experiments this film drive is pulled out of the system and opened in the darkroom. The shutter has a diameter of 2.5 inches and minimum opening time of 40 milliseconds.

3.4 In-Line Holocamera. Few changes are required in order to convert the double-beam holocamera to the simpler in-line system shown in Fig.1b. This conversion is achieved by removing the separating beam splitter, transferring the spatial filter from the reference beam to the subject beam and rotating the film drive-shutter assembly towards the relay lenses. This holocamera has already been used in the in-line configuration during the comparative study described by Katz et al (1982) and an example of the resulting holograms is presented in Fig.8.



#### 4. Physical Structure.

The Underwater Holographic Camera is contained in two separate housings, an underwater pressure vessel and an above-ground power supply and control rack. These are shown in the photograph of Fig.2. Electrical cables connect the control rack to the submersible camera; these contain the high voltage supply for the flashlamp, the high voltage trigger cable, 110 V.A.C. and low voltage power and signal functions and trigger functions. This cable is one hundred fifty feet in length and is encased in plastic hose for water tightness. The cable assembly is permanently connected to the submersible portion but can be disconnected easily from the control rack for transport. The control rack itself is capable of being crane lifted and is provided with a weather resistant plastic cover. The operational details of the control rack are described in the next section.

The physical arrangements of the submersible holocamera portion are shown in the cross-sectional drawings of Figs.6a,b. The tank proper, as can be seen, is about three feet long and made of 24 inch diameter schedule 20 steel pipe. Each end of the tank is fitted with an elliptical head. The join between these tank ends and the tank itself is made by a 24 inch Marmon clamp. A rubber O-ring provides the pressure seal; to ensure a smooth clamping action and seal the clamp ring material is made of stainless steel and welded to the pipe material.

By this means a reasonably lightweight structure is achieved for the end caps so that a single person without assistance can easily open up or close the submersible structure. For ease of handling, guide pins are mounted on each end to help bring the mating surfaces together.

The tank submersible body is supported on a rigid welded framework of square stock supported by rubber tired wheels, two of which swivel. Provision is made to add ballast in the form of lead bricks to achieve negative buoyancy in sea water.

The most noticeable feature of the structure is of course the optical return path; this is clearly seen in Fig.2 and in the cross-section of Fig.6. In this latter drawing the return optical path is shown rotated 90° for clarity. It may be seen in Fig.6a that front surface mirrors are mounted at each leg of this path; these are individually adjustable and, of course, sealed. The test volume length shown is about fourteen inches less the space occupied by the two optical flats separating the test fluid under pressure from the interior of the holocamera. This return path is made of PVC schedule 40 four inch pipe and fittings. An auxiliary steel brace is provided to support the free end of the return path as can be seen in Figs.6a,b. The underwater assembly weighs about 1000 pounds weighted sufficiently to sink.

No elaborate rigging nor packaging system is believed necessary. A simple rope sling is intended to be used for lifting and if long distance air transport is necessary, a soft mounted pallet will be required.

Two access nipples for electrical leads are provided but only one is currently in use. It is readily possible therefore, to contemplate a concurrent piggy-back instrument to be used with the underwater holocamera.

##### 5. Control Circuits and Operation.

Electrical control of the holocamera is divided between two stations, a panel rack containing all user operated controls and monitors, and remote

units located inside the submersible tank. Figure 7 is a sketch showing the location of various electronic control functions, and Appendix II contains detailed layouts and schematics of the control system. Figure II.1 shows the overall layout of the control rack, Figs. II.2 - II.10 show details of its component circuitry, and Figs. II.11 - II.16 show details of the remote circuits inside the tank.

The 900 volt power supply to the flashlamp trigger system is located in the laser exciter chassis of the panel rack. This voltage is supplied to a remote series injection trigger transformer (see Fig. II.14), which then sends a 20000 volt pulse to the flashlamp initiating main power discharge. The main power capacitors, which store approximately 1500 Joules at 4500 volts for discharge through the flashlamp, are also located in the panel rack. A potentiometer on the exciter circuit board allows precise control of the flashlamp discharge energy. Figures II.2 - II.5 provide detailed schematics of the laser exciter electronic components.

The timing of the Pockels cell pulses, the shutter operation, and the automatic film advance are all initiated by the flashlamp triggering pulse. Control of the time delay between flashlamp triggering and the first Pockels cell pulse (delay 1), the time delay between the first and second Pockels cell pulses (delay 2), and the pulse energy are all controlled at the timing chassis of the panel rack. These signals are sent to the remote pulser units, which then send high voltage pulses to the Pockels cell at the proper times. A pulser output monitor inside the tank can be connected directly to the control panel oscilloscope to allow observation of the Pockels cell high voltage pulses. The automatic shutter opens with each Pockels cell pulse, exposing the film to the corresponding laser pulse. The film advances after

the second Pockels cell pulse. Figs.II.6 - II.13 provide details of the timing chassis and its component circuitry.

Auxiliary electronic devices include a leak detector and a photodiode. The leak detector is located beneath the optical table inside the tank. Any leak will cause the device to send out a signal, which is amplified by a circuit inside the tank, then sent on to the control panel to light a warning lamp. The PIN diode photocell is mounted on the optical table. Its output signal is relayed to the control panel, allowing direct observation of the laser output on the oscilloscope. The system has the capability to use two photodiodes, but at present only one is used (see Figs.1a and b for location of photodiode in the holocamera). Figures II.15 and II.16 supply details of photocell and leak detector connection and amplifier circuits. Figure II.15 shows also the 110 V.A.C. power supply to the submersible tank, for use by the shutter, film drive, cooling water pump, and alignment He-Ne laser.

Operation of the holocamera proceeds as follows (refer to Fig.II.1):

1. Turn on AC power to tank circuits. This initiates flow of cooling water, and enables shutter and film drive to operate.
2. Turn on high voltage supply to Pockels cell pulser. Monitor this voltage and adjust to approximately 4.4 kV.
3. Turn on power to laser exciter chassis.
4. Turn on trigger power. *840 V on TRIGGER Power SUPPLY*
5. Charge main power capacitors. Their charge level is monitored by the "Flash Power Voltage" meter on the panel rack. Full

charge is set at about 4.2 kV. (and is adjustable by a small pot in the lower rack which is typically set at ~50")

6. After fully charging the capacitors, the system is triggered by pushbutton. Laser pulses and/or Pockels cell high voltage pulses can be observed on the oscilloscope.
7. Allow system to cool for several minutes before recharging for next laser firing. (See Koechner (1976) for details on cooling.)

#### 6. Reconstruction System

Holographic reconstruction is accomplished by illuminating the hologram with a suitable coherent beam, causing the recorded diffraction pattern to create two three-dimensional images, a real and a virtual image. The light source in the present system is a 5 milliwatt He-Ne laser, whose output beam is expanded by an objective, spatially filtered by a pinhole, and collimated by a lens. This collimated beam illuminates the hologram, which is mounted on an x-y-z vernier carriage.

In reconstruction of double-beam holograms (Figs.9a, 10a), the illuminating beam is the conjugate of the original reference beam, that is, passes through the film from the opposite side and directed opposite to the original reference beam. This illumination projects a real pseudoscopic (depth inverted) image field along the axis of the original subject beam. A magnifying objective, placed on this axis inside the real image field, is used to focus any desired cross-section onto a closed circuit TV vidicon, so the image of that area can be inspected on the TV monitor screen. The x-y-z control of the hologram mount permits focusing of any point in the reconstruction field

onto the vidicon. Realization of a suitable reconstructed image of the preliminary double-beam holograms has not yet been accomplished.

The in-line reconstruction system (Figs.9b,10b) follows the same principles as the double-beam system, but allows a much simpler geometry. The conjugate illuminating beam here strikes the hologram on a normal, projecting the real image along the same axis. Observations are again made in the real image field. Figure 11 shows the reconstructed image of a pair of 20 micrometer nuclei. Magnification is 220. Note that this image is from reconstruction of the hologram shown in Fig.8b (see Ref.10 for additional reconstructed images).

## 7. Discussion.

The preceeding sections have described the mechanical and optical components of the Underwater Holocamera. To date the holocamera has been used in the comparative studies of Katz et al (1982), done as a part of the present contract. More recently off-axis holograms have been made of simple objects in the test volume. Reproductions of holograms of both types are shown in Fig.8. Many reconstructions of this in-line type were made for the work of Ref.10 and an example of one of these is shown in Fig.11. We have not shown a reconstruction of the off-axis hologram only for press of time. We had earnestly hoped to make an underwater test of the entire system but we were not able to do so in the time remaining to the project. The off-axis hologram of Fig.8 was made with a water environment by surrounding the test volume of the return optical path with a flexible dam which was then filled with water.

In the immediate future the off-axis reconstruction system will be final-



ized and completed for routine analysis. We also hope to exercise the Underwater Holocamera both in the laboratory, the Institute swimming pool and with additional support, in local ocean waters the summer of this year. We anticipate that this new facility will have a major impact on understanding both of laboratory flows of a wide spectrum as well as natural waters.

8. Acknowledgments. An extensive design engineering and fabrication task such as is represented in the Underwater Holocamera require the efforts of many people for a successful outcome. We should like to express here our gratitude to Elton Daly and Joe Fontana of the Keck Hydraulic Laboratory staff, George Yamaguchi of the Central Engineering staff, Dr. Haskell Shapiro of Shapiro Scientific Instruments, to Sue Berkley and her staff for myriads of details and finally to Justin McCarthy and Thomas Huang of DTNSRDC for their unfailing and enthusiastic support.

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- |                     |                                      |                                       |
|---------------------|--------------------------------------|---------------------------------------|
| 1. BACK MIRROR      | 8. REFLECTOR                         | 15. MICROSCOPE OBJECTIVE              |
| 2. IRIS APERTURE    | 9. FRONT MIRROR - SAPPHIRE ETALON    | 16. COLLIMATING LENS                  |
| 3. POLARIZER        | 10. TRIGGER TRANSFORMER              | 17. SPATIAL FILTER - $10\mu$ PIN HOLE |
| 4. POCKEL'S CELL    | 11. ND FILTER                        | 18. RELAY LENSES                      |
| 5. POLARIZER        | 12. BEAM SPLITTER (4% REFLECTIVITY)  | 19. GLASS WINDOWS                     |
| 6. RUBY ROD         | 13. PIN DIODE                        | 20. DIFFUSER                          |
| 7. XENON FLASH LAMP | 14. BEAM SPLITTER (50% REFLECTIVITY) | 21. SHUTTER                           |

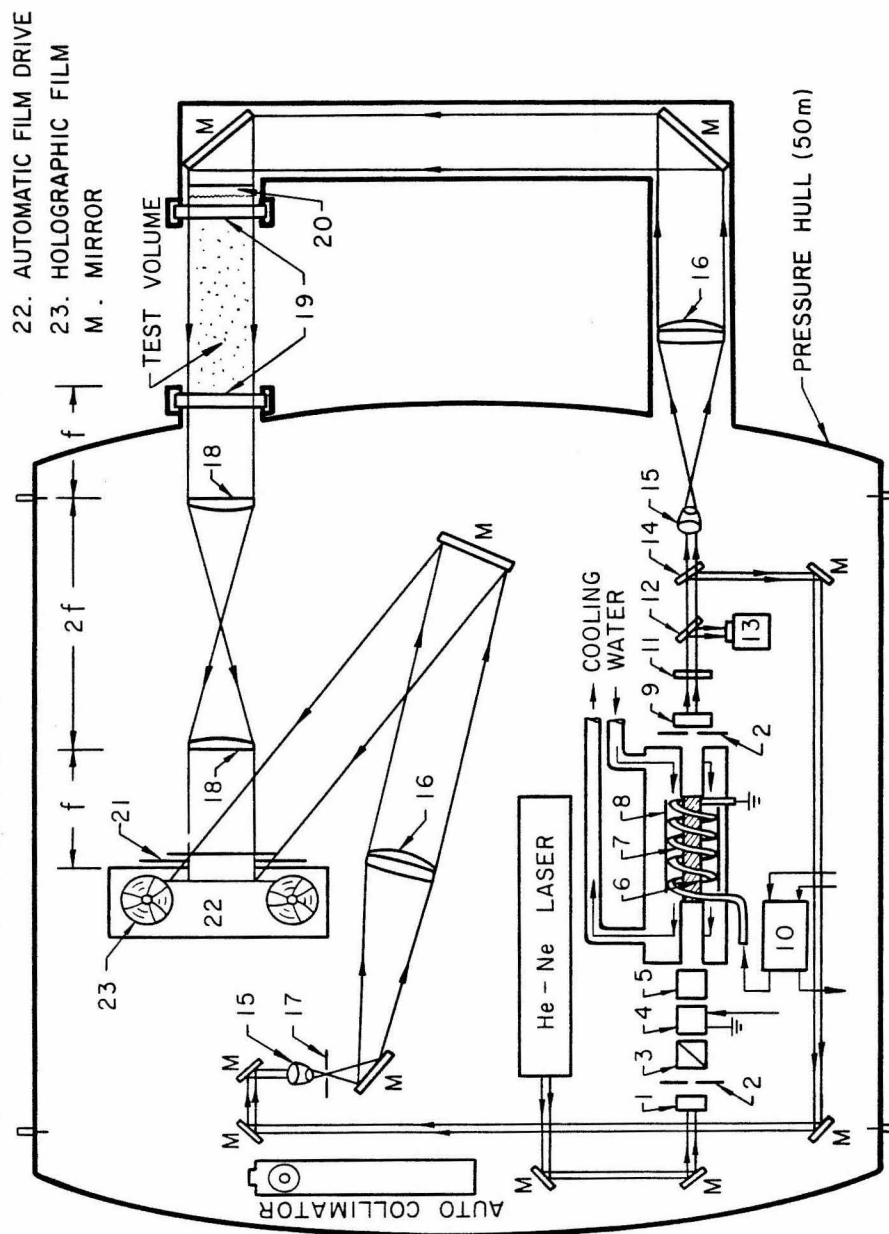


Fig.1a

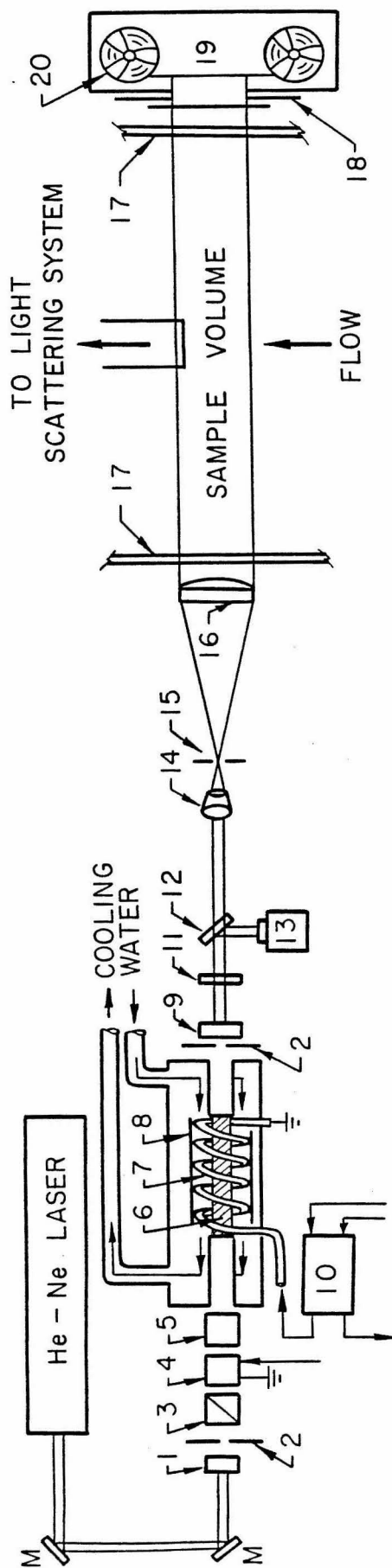


Fig.1b



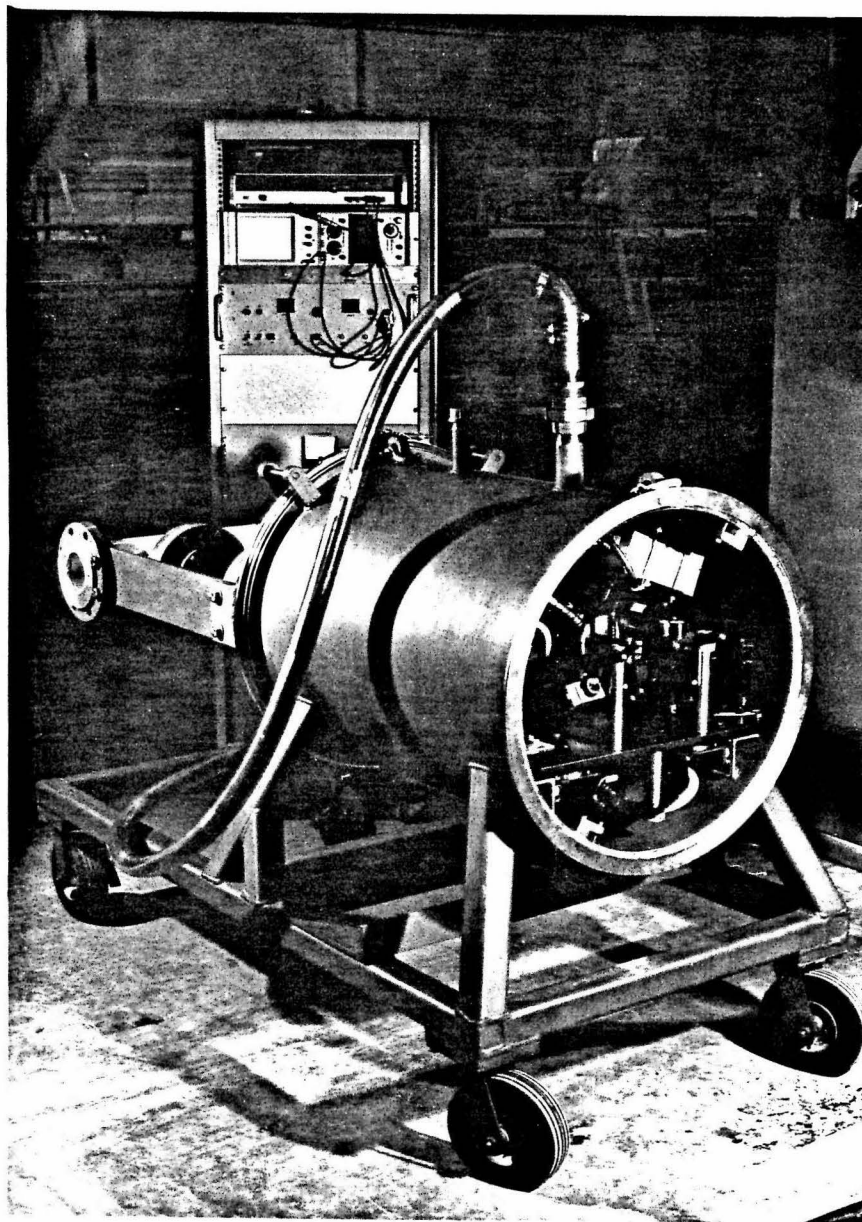


Fig.2

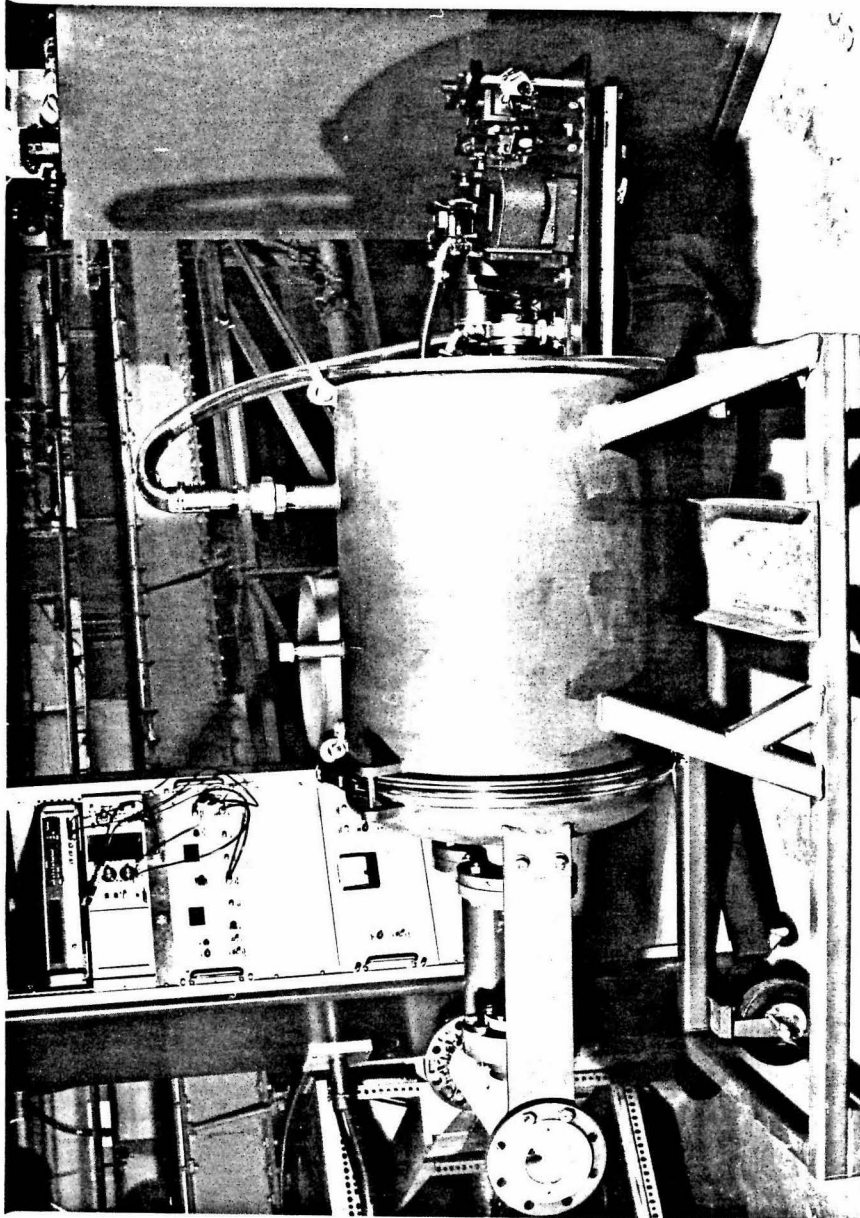


Fig. 3

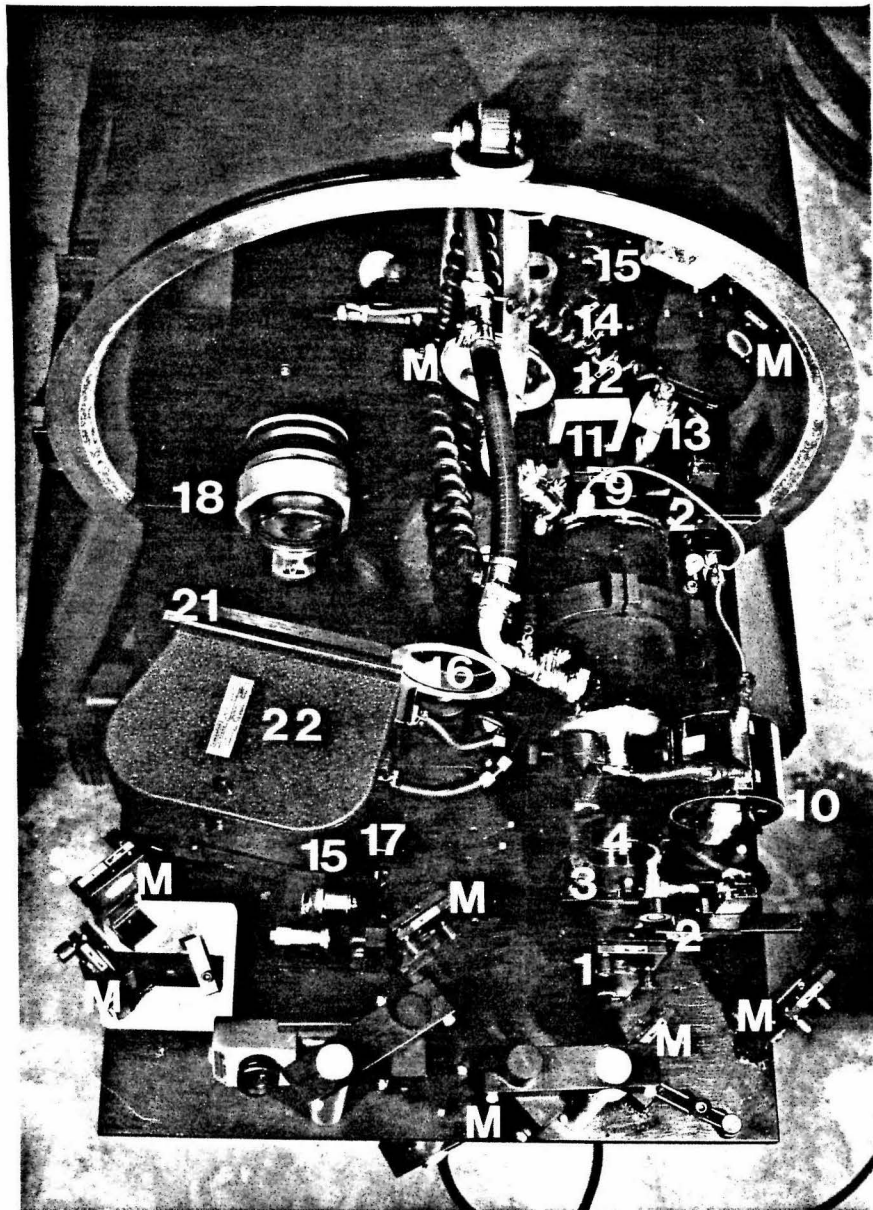


Fig.4

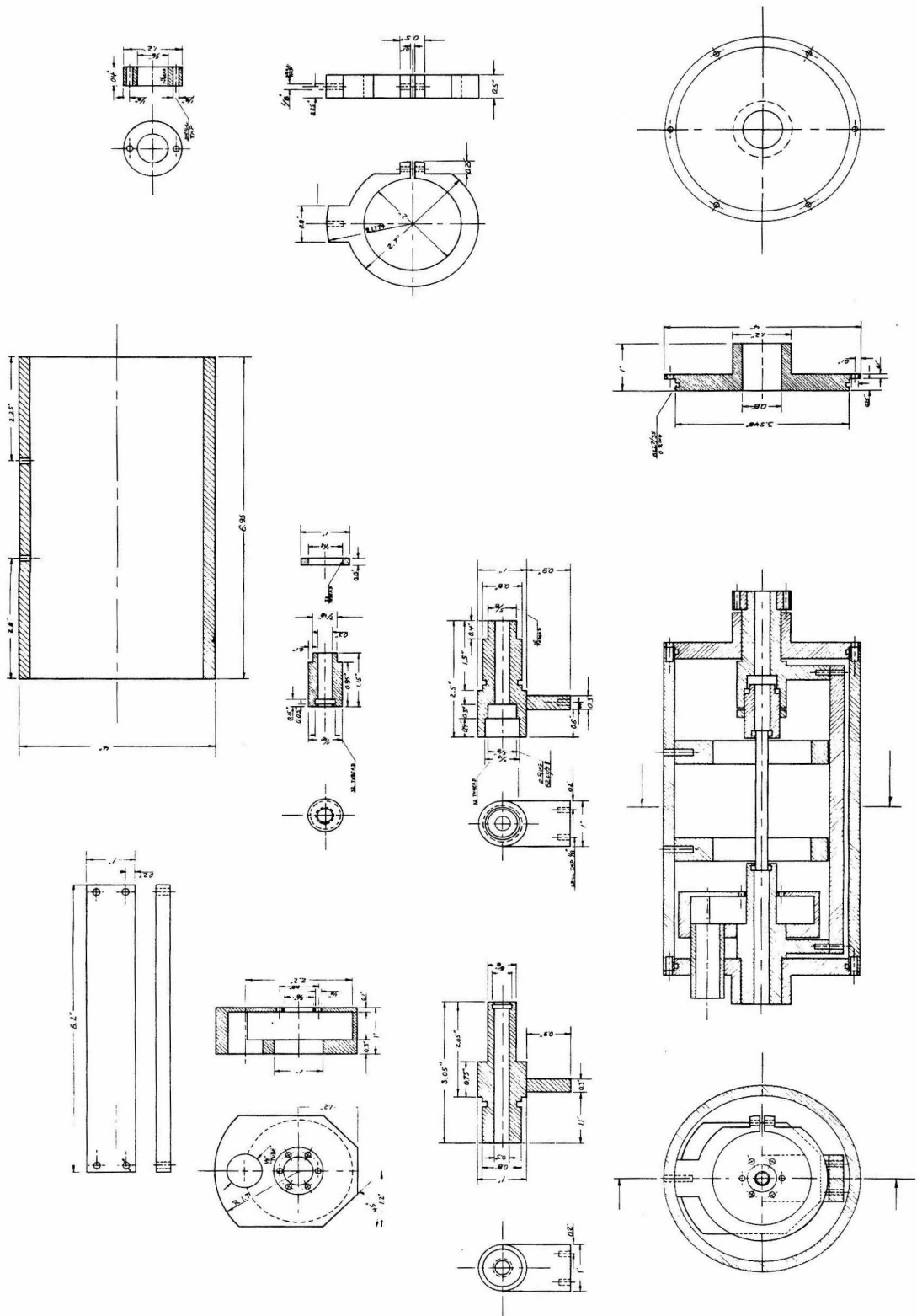


Fig. 5a

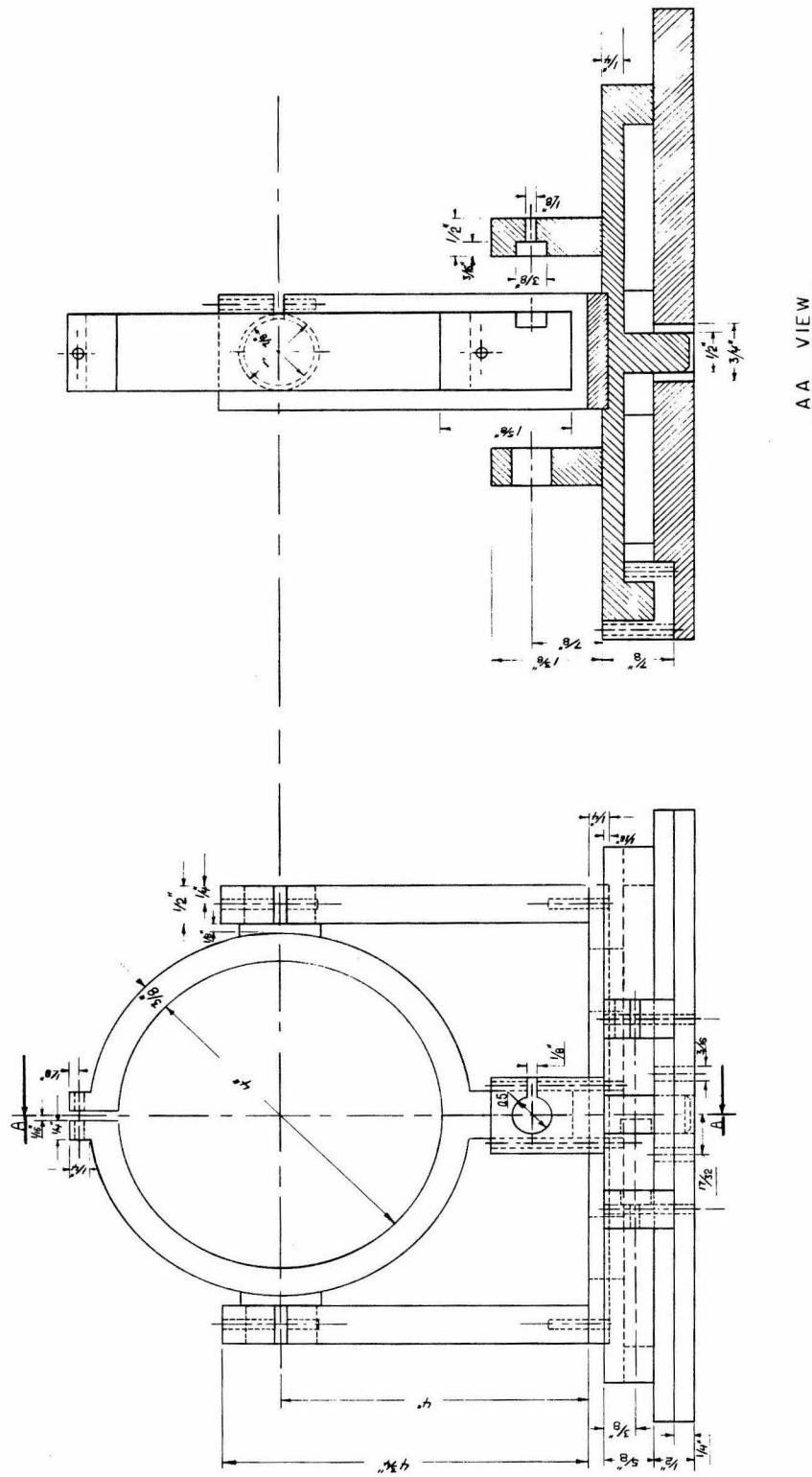


Fig. 5b

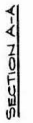


Fig. 6a



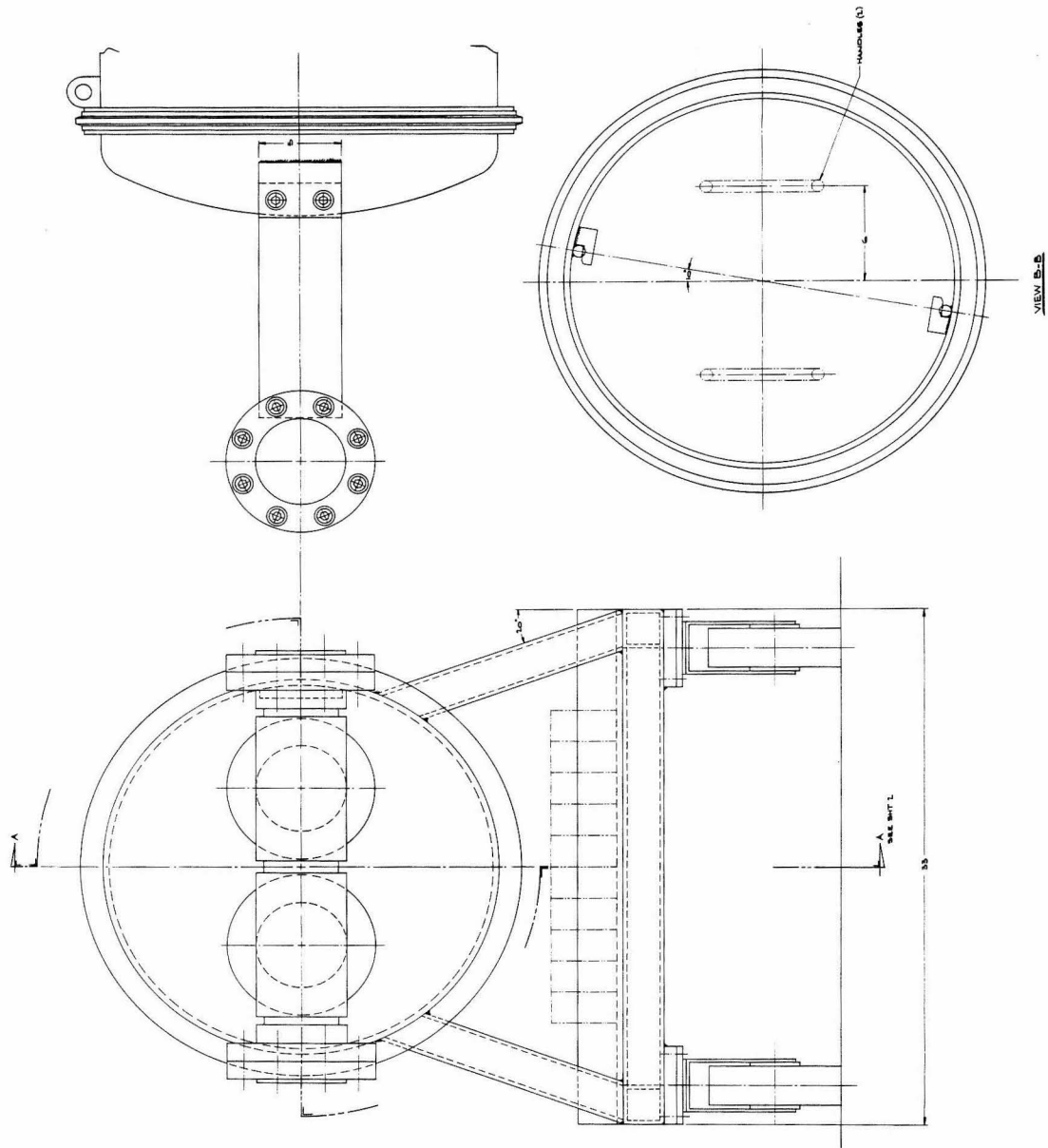


Fig. 6b

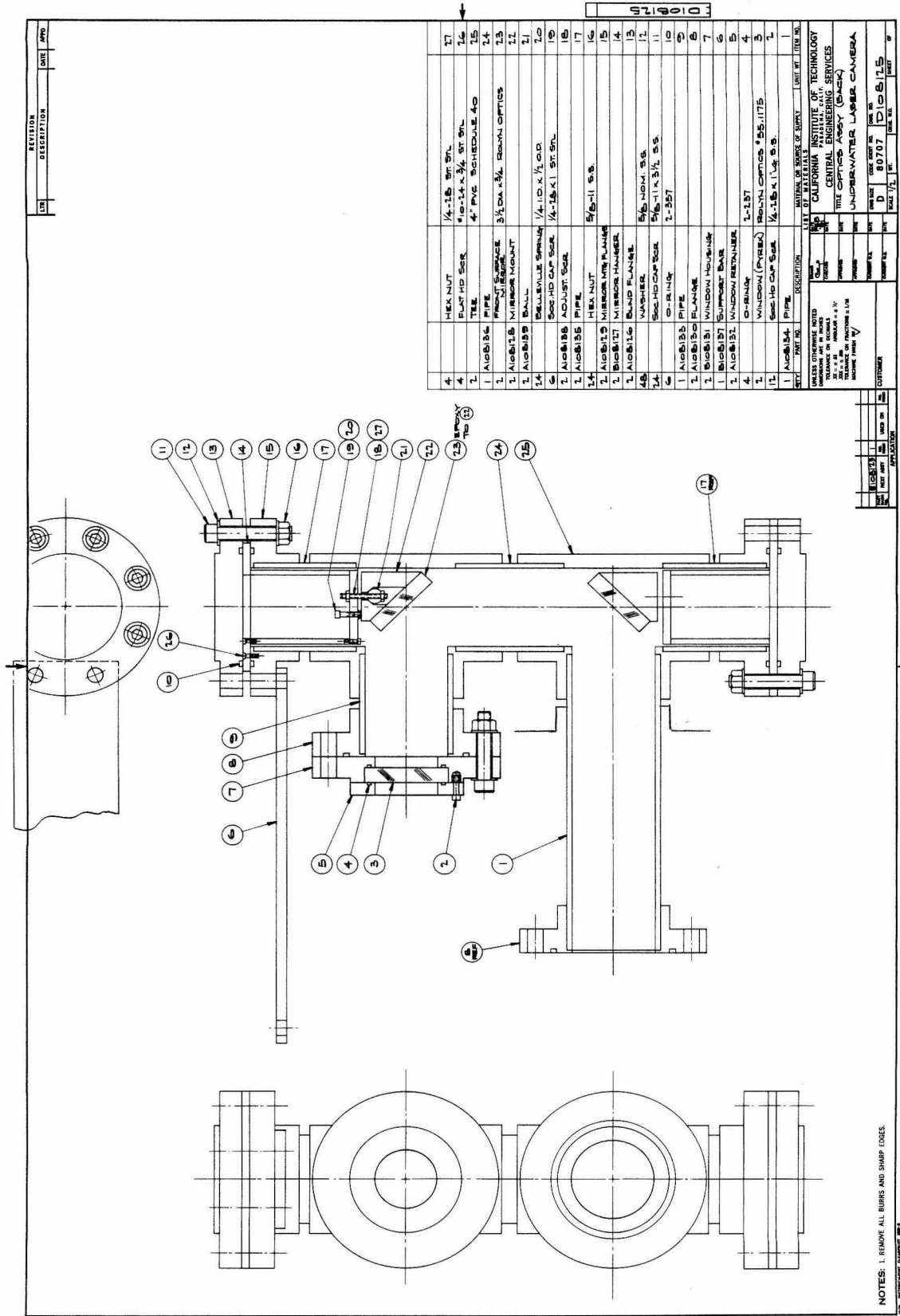


Fig. 6c

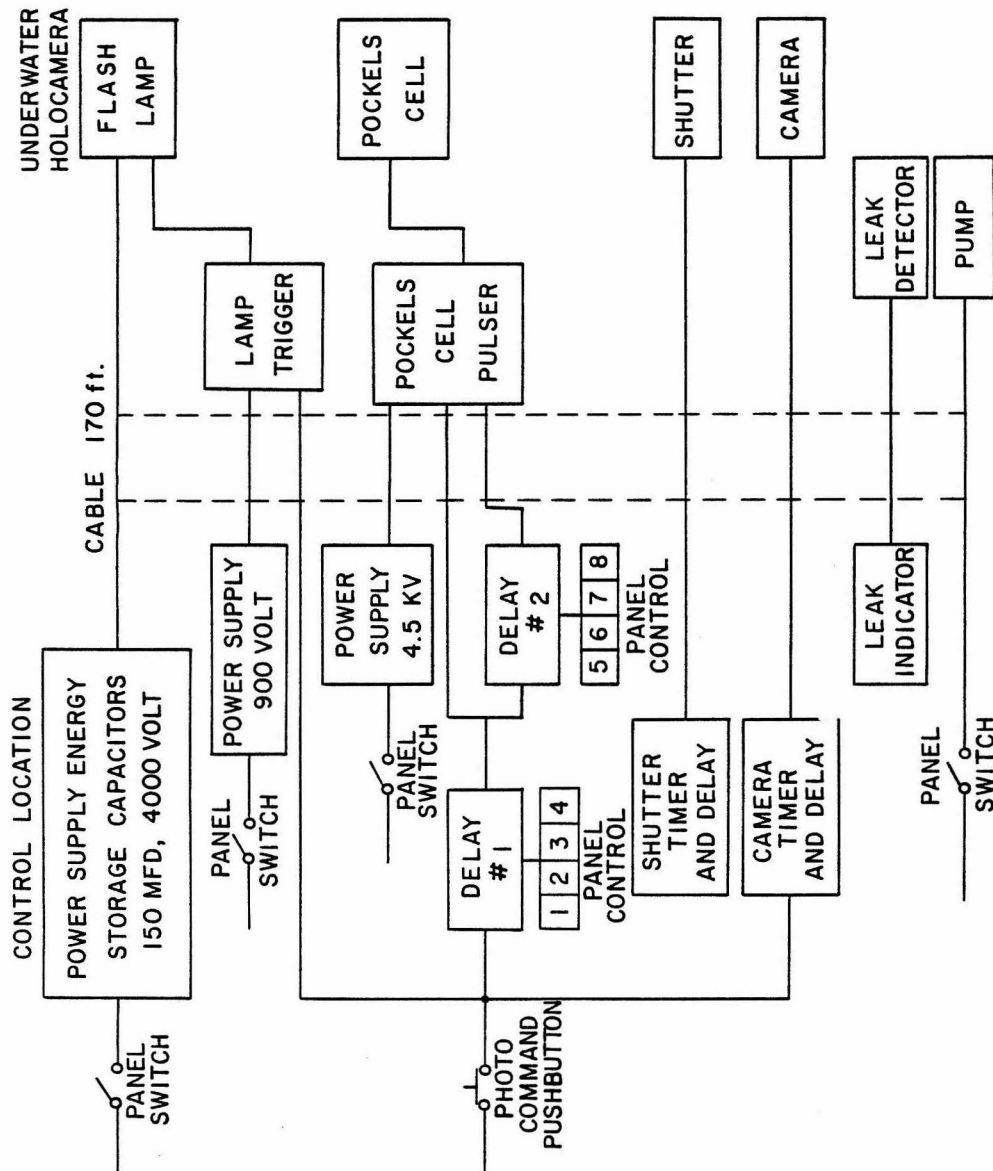


Fig. 7

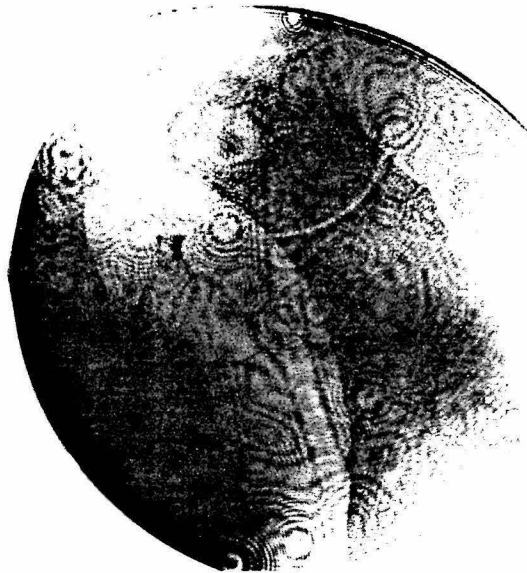


Fig. 8a

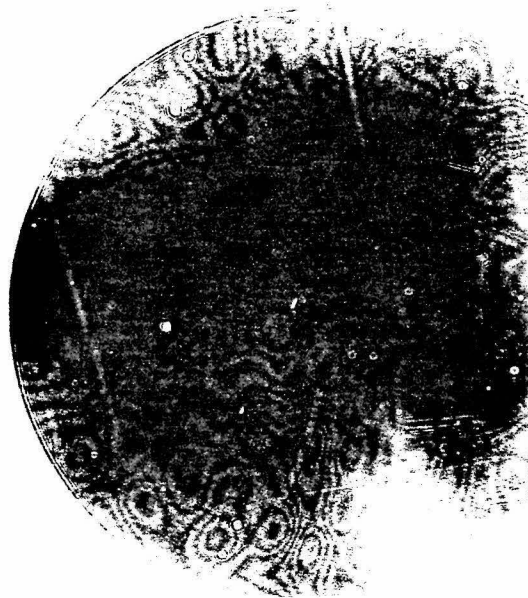


Fig. 8b

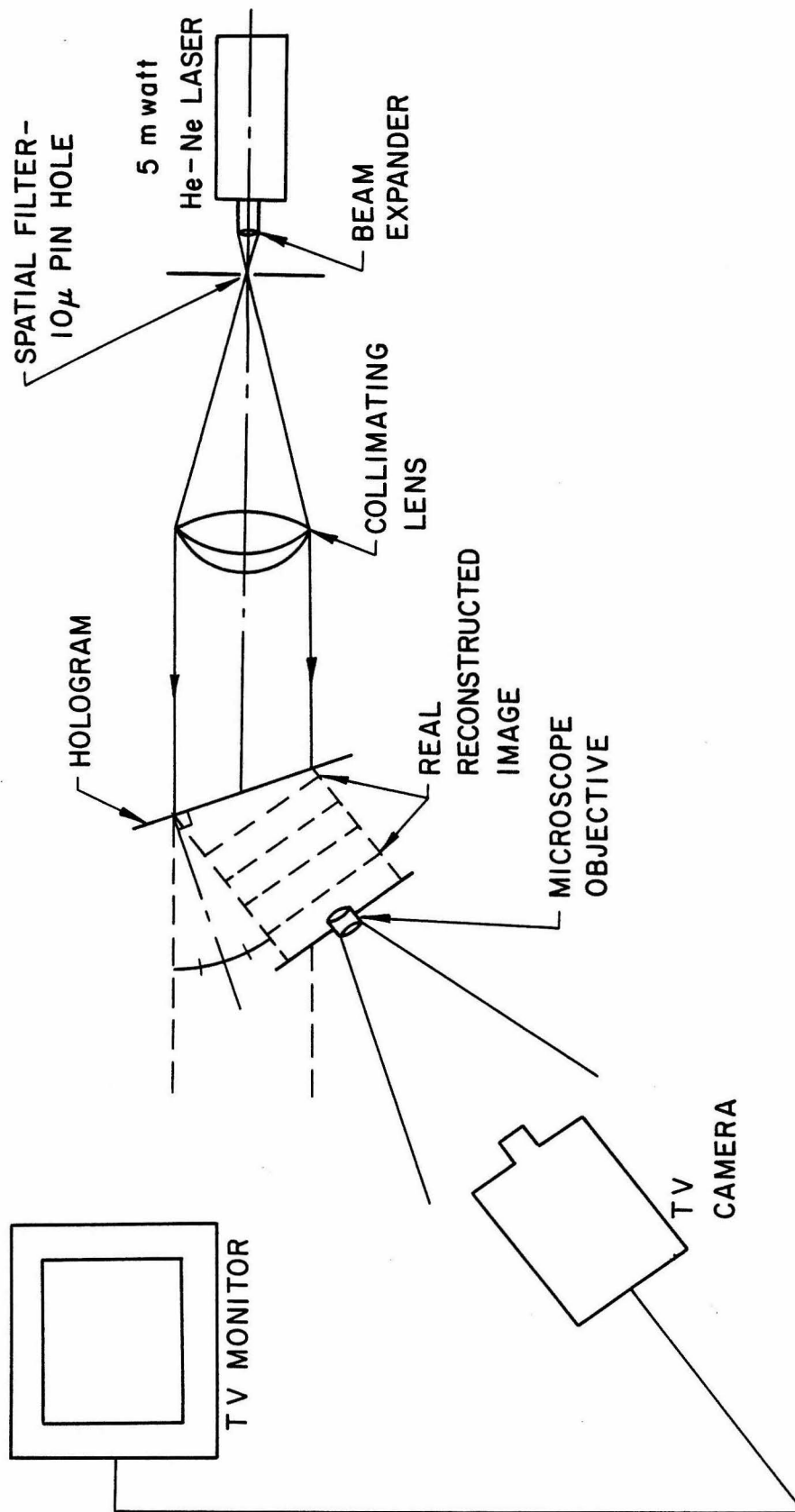


Fig. 9a

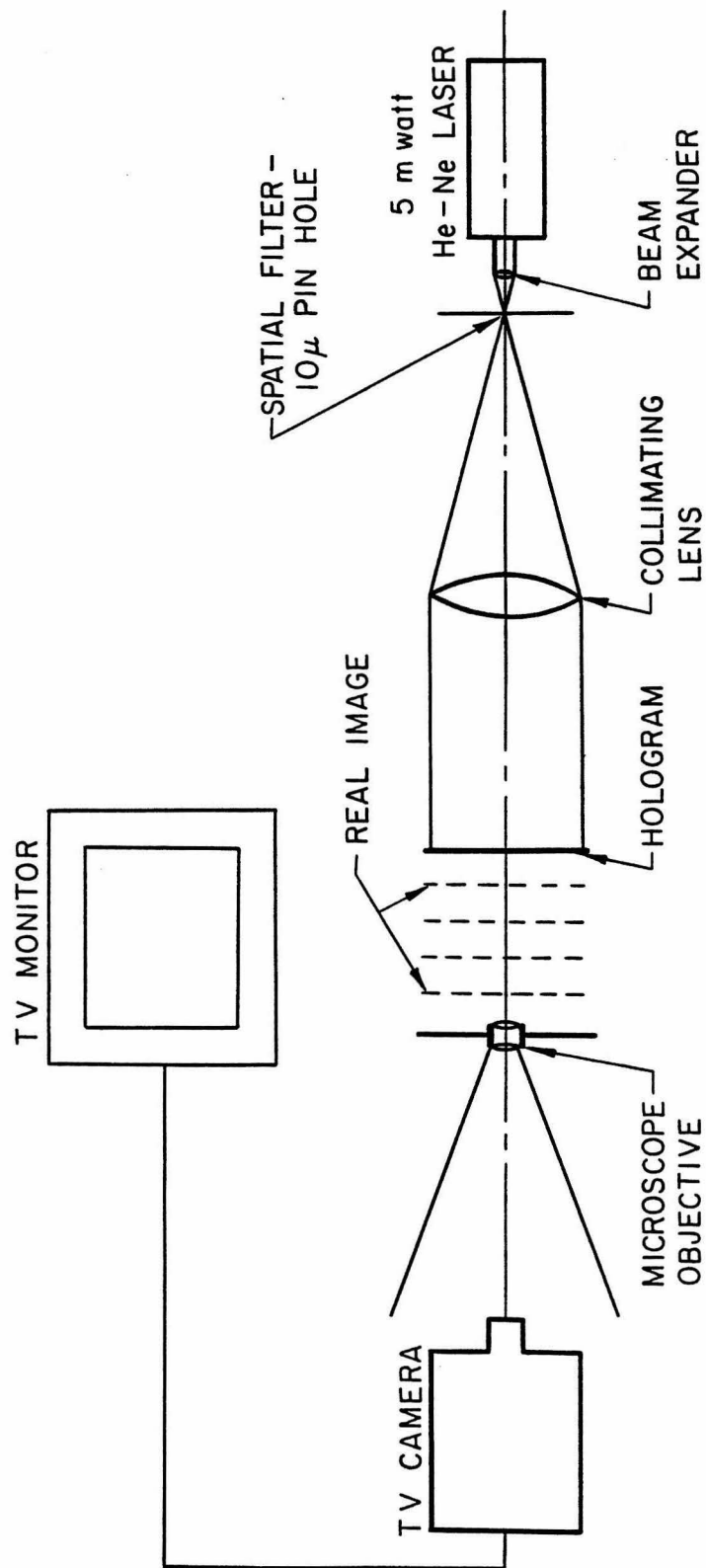


Fig. 9b



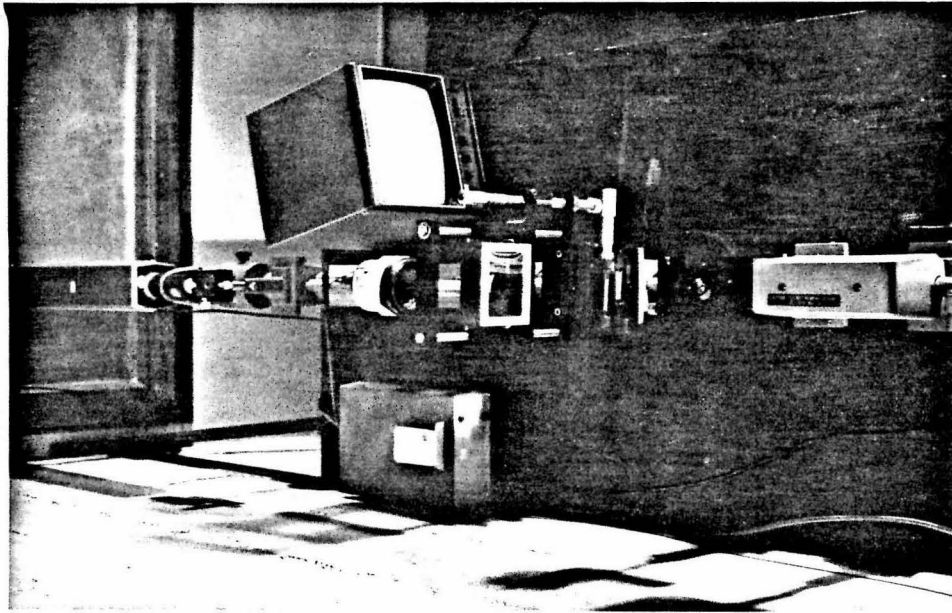


Fig. 10b

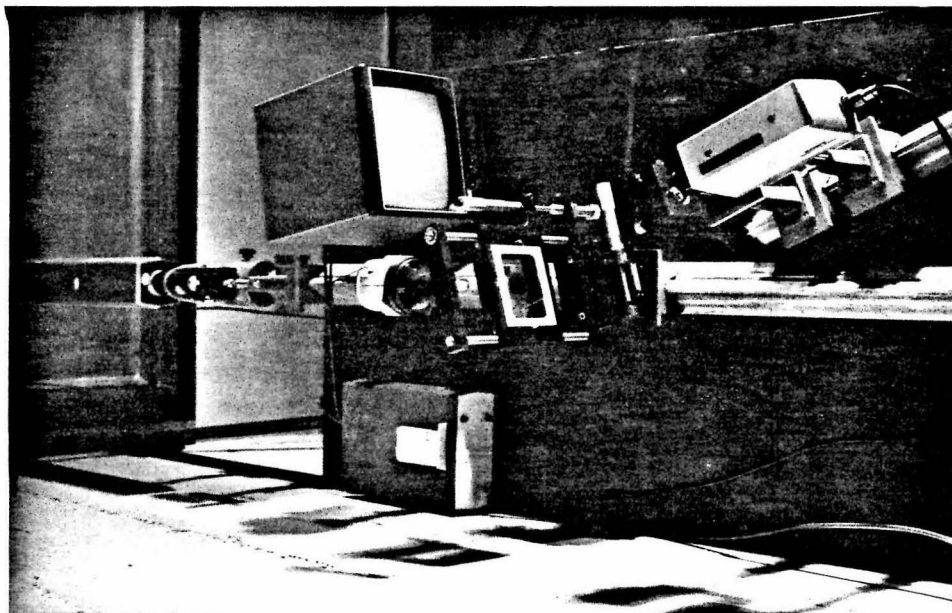


Fig. 10a

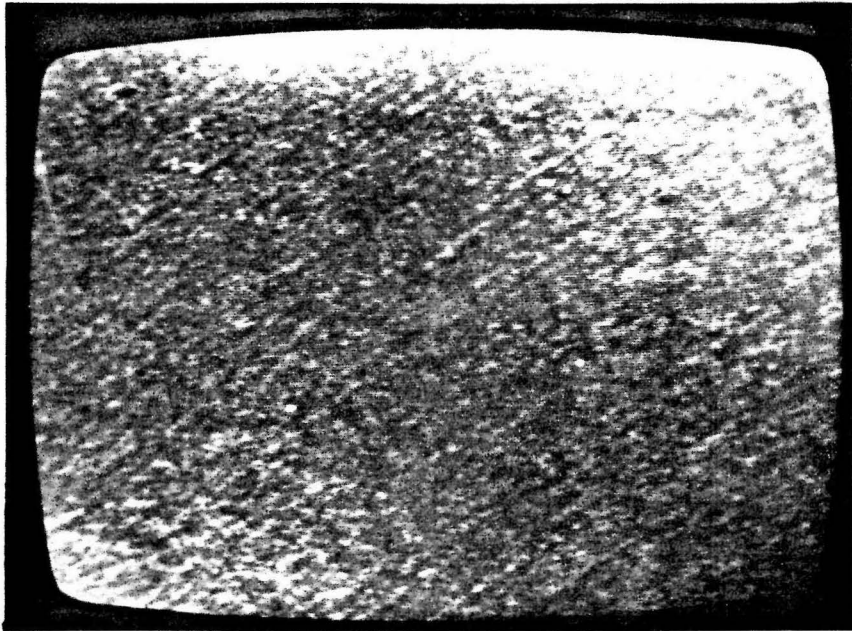


Fig.11

APPENDIX I

List of Components and Suppliers for  
Underwater Holocamera

VENDOR	ADDRESS & PHONE NUMBER	ITEMS	MODEL NUMBERS (if any)
Ardel Kinematic	PO Box 139 Stamford, CT 06904 (203)348-4247	Polar Rotator	RT-31V
A-F Sales	1000 E. Walnut St. Pasadena, CA 91106	RCA Silicon Vidicon  RCA Video Monitor	TC1005/H01  TC1100
Buckbee-Mears Co.	245 E. 6th Street St. Paul, Minn. 55101 (612) 226-6371	Pinhole Apertures, 11 Micron size, nickel	
Cal-State Seal Co.	13891 Nautilus Drive Garden Grove, CA 92643 (213)587-8183	O-Rings	2-357 N674-70 2-237 N674-70
Cetec Electronics	5610 E. Imperial Hwy. South Gate, CA. 90280 (213)773-6521	Multiple pin connector  BNC Connector	165-10  309-28000
Cole-Parmer Instrument Co.	7425 N. Oak Park Ave. Chicago, Ill. 60648 (800) 323-4340	Pump - Lab-Puppy	C-7097-20
Ditric Optics	312 Main Street Hudson, MA 01749 (617)562-9373	3" dia., 3 cavity, 12mm band- width, 694.3mm, interference filter	
Dow Radio, Inc.	1759 E. Colorado Pasadena, CA 91106 (213) 793-1195	integrated circuits Dow Pak integrated circuits  Belden wire	MC 14518 J0069  9259
EG & G Electro- Optics	14531 Hamlin Street Suite 201 Van Nuys, CA 91411 (213) 988-2000	Series Injection Trigger Transformer	TS-146A
Ealing Corp.	Suite 203 900 Birch Street Commerce Park Newport Beach, CA 92660 (714) 833-9826	round plane mirror 1" dia.  $\lambda/10$ flatness optical flats 101.6mm dia.	23-5218  35-8911
Electronic Sup.	2486 3rd Street Riverside, CA (714)626-6791	Belden Coax Cable 9259 RG 50/U	#9259U1000-10
Emcor Products	1600 4th Avenue N.W. Rochester, Mn. 55901 (507)289-3371	Rack, 68 3/8" by 25 1/2" by 61 1/4" Side frames Door Top	IFR-12GA 1SP-126A 7DU-61B-CH PH-21

VENDOR	ADDRESS & PHONE NUMBER	ITEMS	MODEL NUMBERS (if any)
Empire Electronic Distributors, Inc.	37 E. Union Pasadena, CA 91103 (213) 796-0121	Cable Cable Cable Cable	8415 8491 9470 8499
Foothill Tool & Machinery	2308 E. Colorado Blvd. Pasadena, CA 91107 (213) 795-8025	screws screws screws	ADB 5002 ADB 50905 0-80-s/B2 sets
Garden Photo Sales, Inc.	1509 N. Gordon St. Hollywood, CA 90028 (213) 461-3587	Beattie 70mm Magazine	
Garrett Ind. Sup.	6015 Randolph Street Los Angeles, CA (213) 724-2222	LS Starrett 2 inch micrometer head	#63P
Hamilton Electro Sales	10912 Washington Blvd. Culver City, CA (213) 558-2131 2149	SCR by General Electric	Part #2N5207
Lasermetrics	196 Coolidge Avenue Englewood, New Jersey 07631 (201) 894-0550	Repairing of Switch Pockel's cell  Polarizer Glan Laser, for 1057 Pockels Cell  Pockels Cell	1057FV (S/N 6688B)  41PGLD-V2 (6943)  1057FV (6943)
Lee Spring Co.	30 Main Street Brooklyn, N.Y. 11201 (212) 855-7136	Music Wire Spring  Springs	LC-026D-5  LC-022 C-7 MW
Newport Corp.	18235 Mt. Baldy Circle Fountain Valley, CA. 92708 (714) 963-9811	Micrometer  Coating, 1" dia., $\lambda/10$ flatness Round Beam-splitter  Coating 1" dia., $\lambda/10$ flatness Round Beam-splitter  Coating, 1" dia., $\lambda/10$ Flatness, Round Pyrex Mirror  Coating, 4" dia., $\lambda/10$ flatness Round pyrex mirror  Mirror Mount  Riser Blocks	SM-05  10B10-BS.1  10B10-NC.1  10D10-DM.4  40D10-DM.4  MM2-1A  RB-MM2-3

VENDOR	ADDRESS & PHONE NUMBER	ITEMS	MODEL NUMBERS (if any)
Newport cont'd		Elevator Base	EB-1
		Base Clamps	BC-2
		Mirror Mount	625A-4S
		Mirror Mount	MM2-1A
		Riser Blocks	RB-MM2-3
		Elevator Base	EB-1
		Base Clamps	BC-2
		Mirror Mount	MM-2A
		Adaptor	A-1.25-1
		Coating, 1 " dia., $\lambda/10$ flat- ness Round Pyrex Mirror	10D10-DM.4
		Mirror Mount	MM2-1A
		Riser Blocks	RB-MM2-3
		Elevator Base	EB-1
		Base Clamps	BC-2
Oriel Corp.	15 Market Street Stamford, Conn. 06902 (203) 357-1600	Lenses, 3", 250mm focal length, achromatic collimat- ing.	Model 4274
		rod holder, 40mm	1241
		Bench rod, precision, 41.5mm long	1232
		Microscope Objective Holder	1356
		3 inch dia. Optical diffuser	4804
		Micro filter optics cleaner	4902 3cans/box
		Optical cleaning pads	4910
		Mirror Mount, for 2" dia mirror	1450
Rolyn Optical	300 Rolyn Place Arcadia, CA 91006 (213) 445-6550	Reticle, 21mm $\phi$ 0.001" increments microscope	70.0166

VENDOR	ADDRESS & PHONE NUMBER	ITEMS	MODEL NUMBERS (if any)
Rolyn cont'd		Achromatic Objective 43:1, E.F.L. -5.0, WD-0.6, N.A. -0165	80.3110
		Microscope objective 18:1, 11 mm E.F.L.	80.3065
		plano convex lens 80mm dia., <del>150mm dia.</del> , 150mm focal length	10.0350
Rudy, J. B.	20950 Brant Avenue Long Beach, CA 90810 (213)636-3403	Beldin Wire	9888
		Belden conductor shielded cable 500 feet	#9261-500
Shapiro Scientific Instruments	3500 E. Coast Hwy. Corona Del Mar, CA 92625 (714)675-1024	Materials to expedite trouble- shooting of Pockel's cell pulser KN-22 Krytron	104-0220
		Engineerng Services in connection with installation of Holocamera	
Space Glass	1539 Howard Access Rd. Upland, CA 91786 (714) 946-2676	Helical Xenon Flashlamp custom made	
		Helical Xenon Flashlamp	
Union Carbide	Crystal Products Dept. 8888 Balboa Ave. San Diego, CA 92123	Ruby Rod 3"long 1/4" diam. & polishing & coating	
Video Suppliers	14526 Crenshal Blvd. Gardena, CA 90249 (213)323-4121	Silicon Control Rectivier	16RIA120
Vincent, A.W. Associates	1255 University Ave. Rochester, New York 14607 (716)473-2232 (800)828-6972	62mm aperture shutter Uniblitz 262	
		25mm basic shutter Uniblitz 225L	225L 0 A 2 T 5

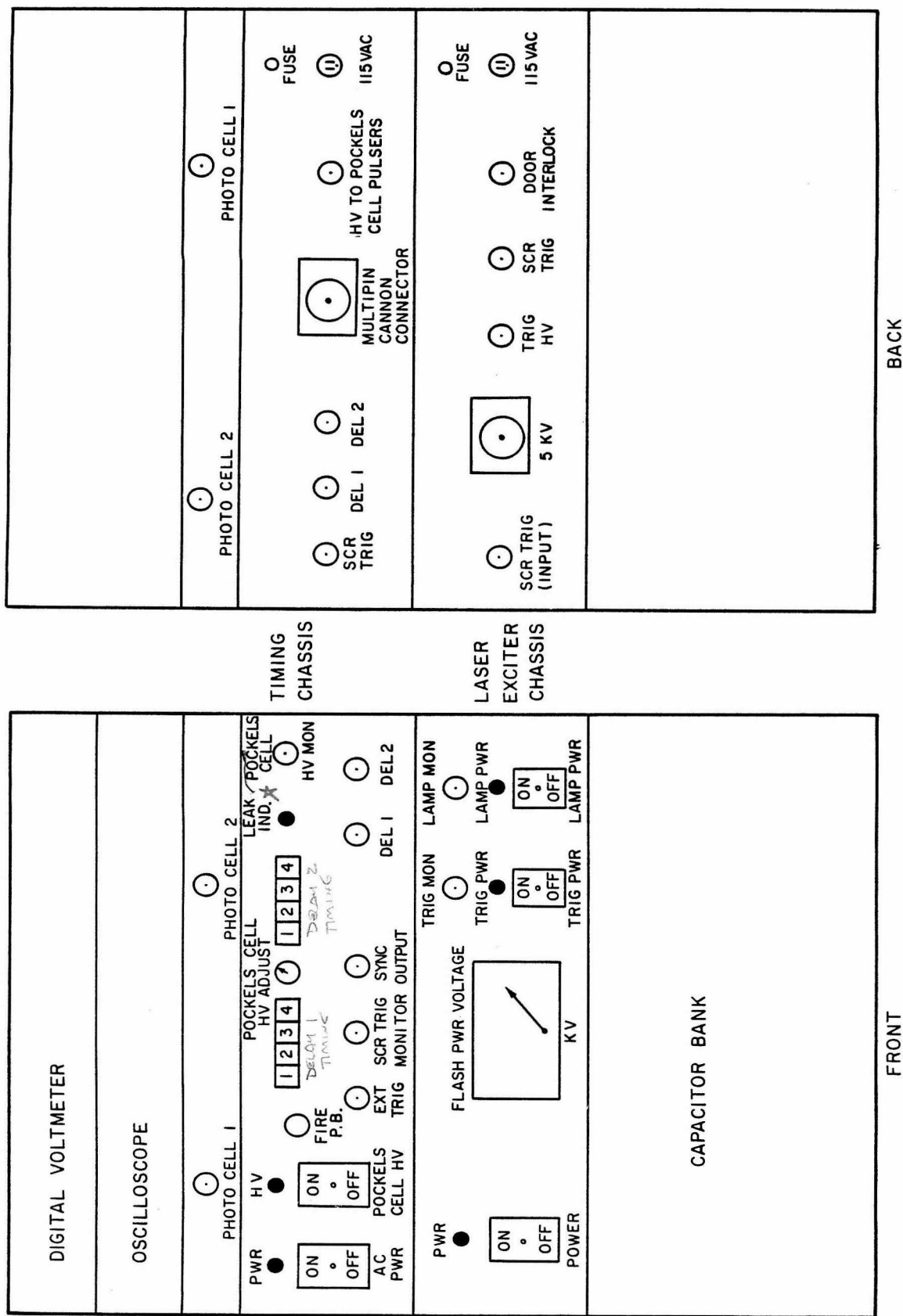


## APPENDIX II

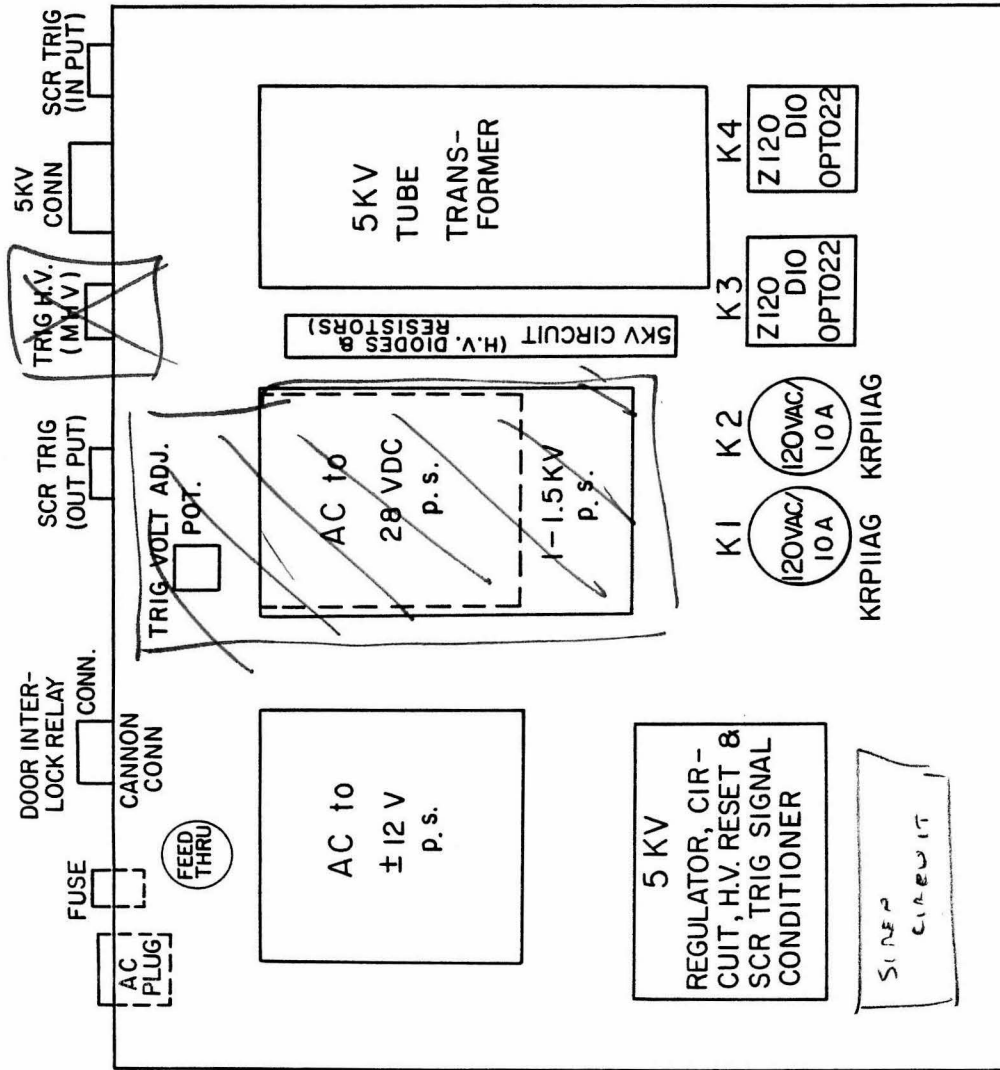
### Control Systems and Circuits

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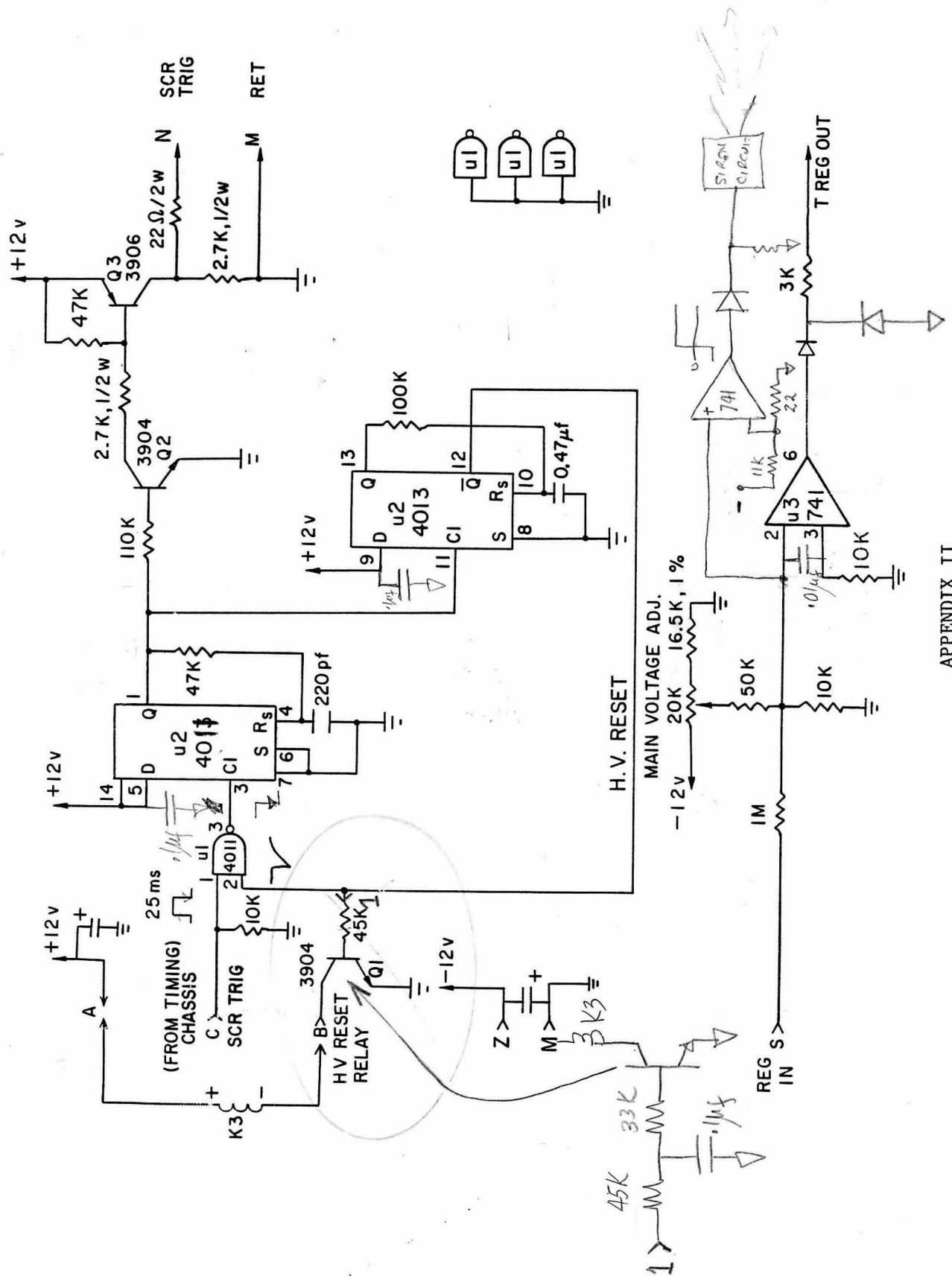
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Figure II-1



## APPENDIX II

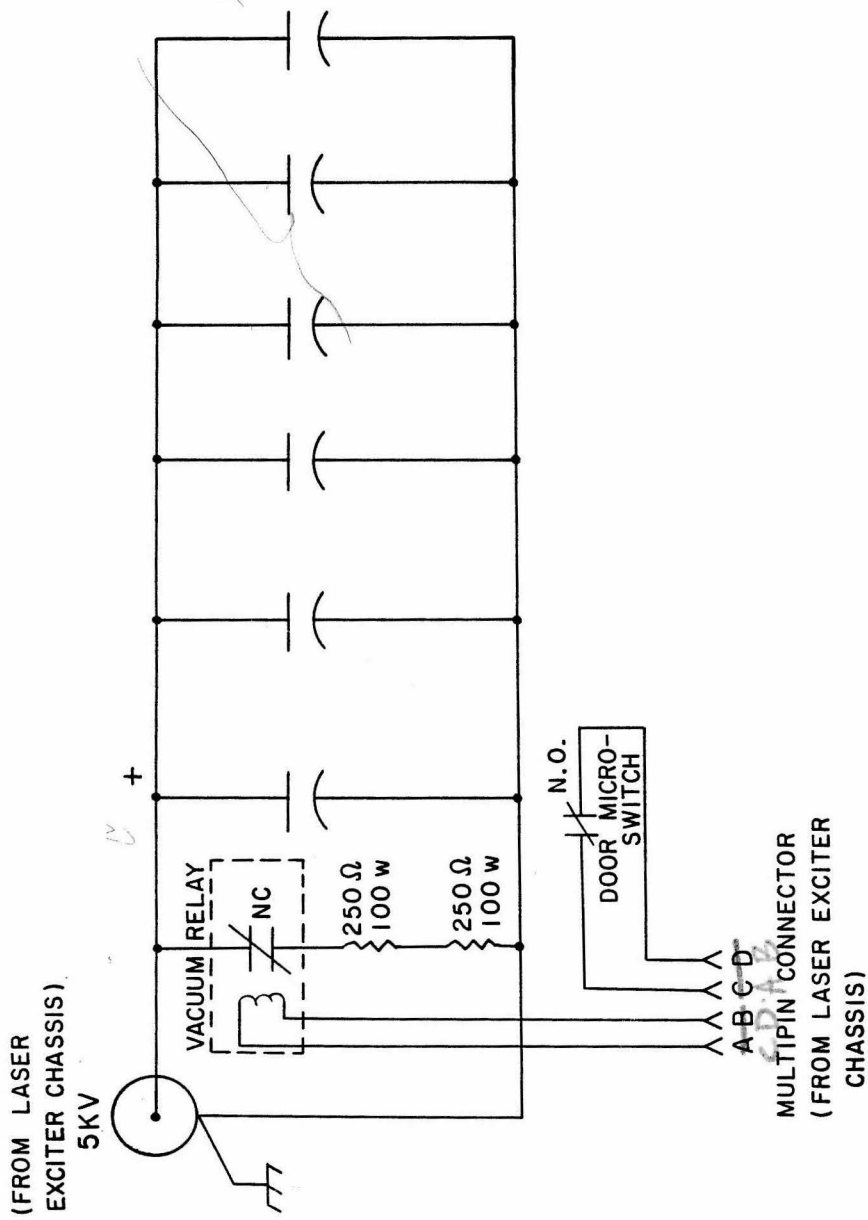
Figure II-2

Figure II-3



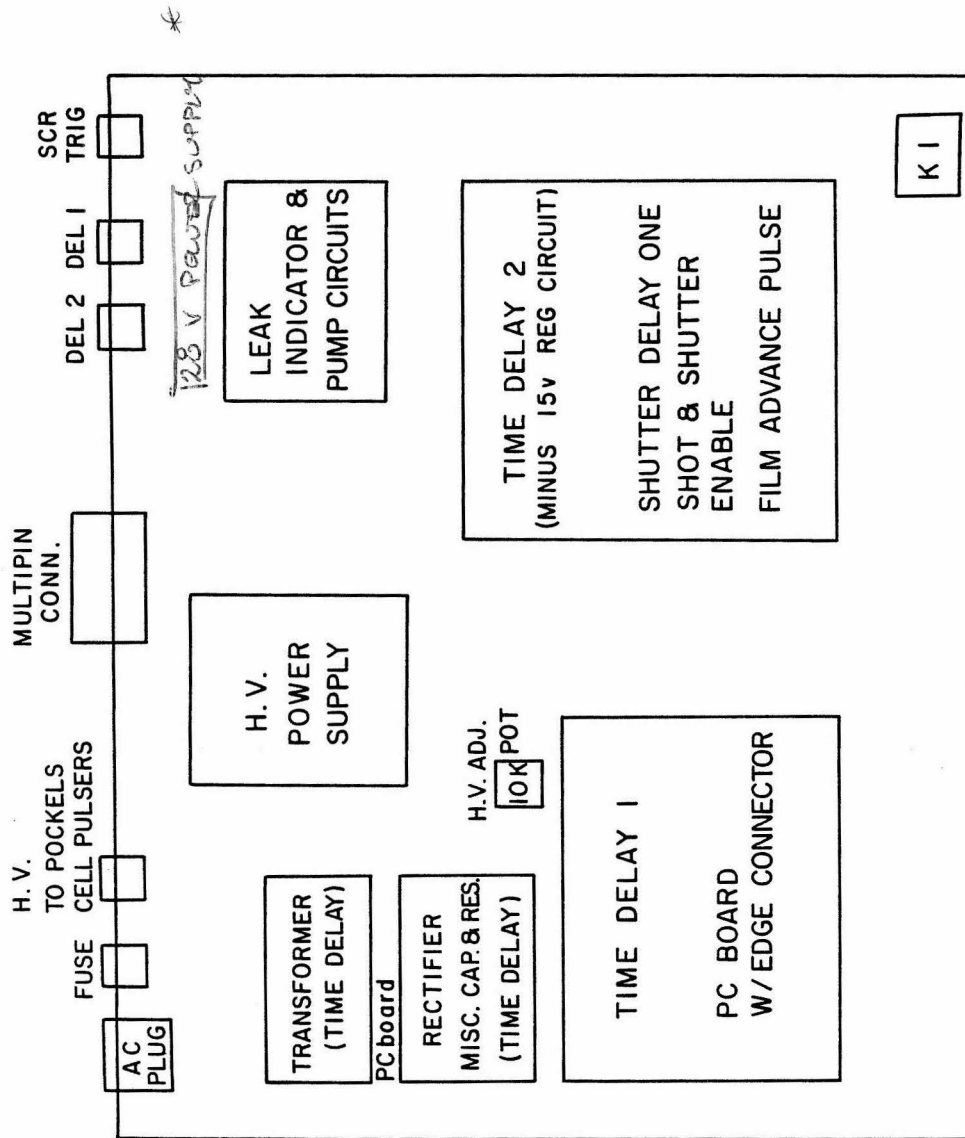
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Figure II-4



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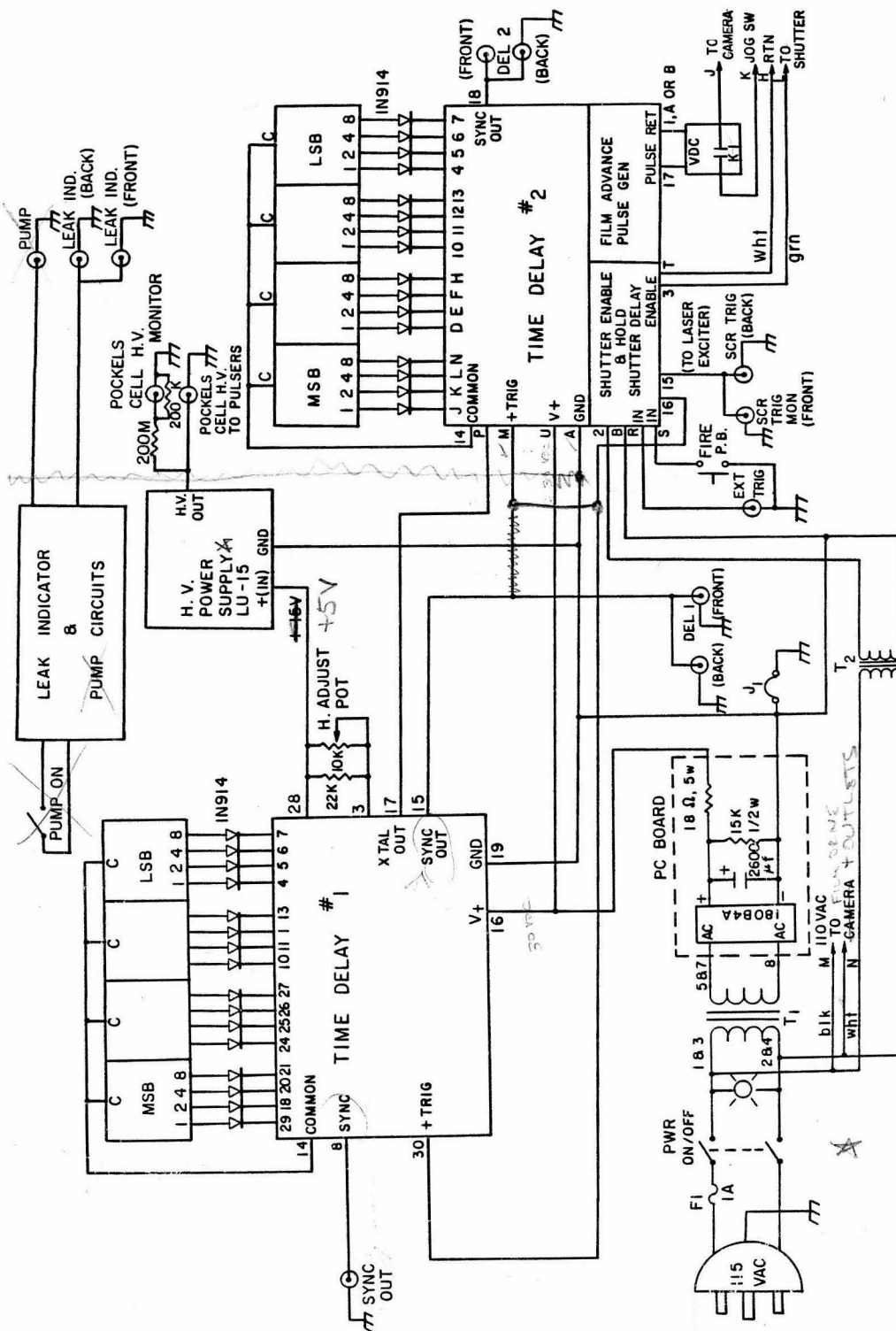
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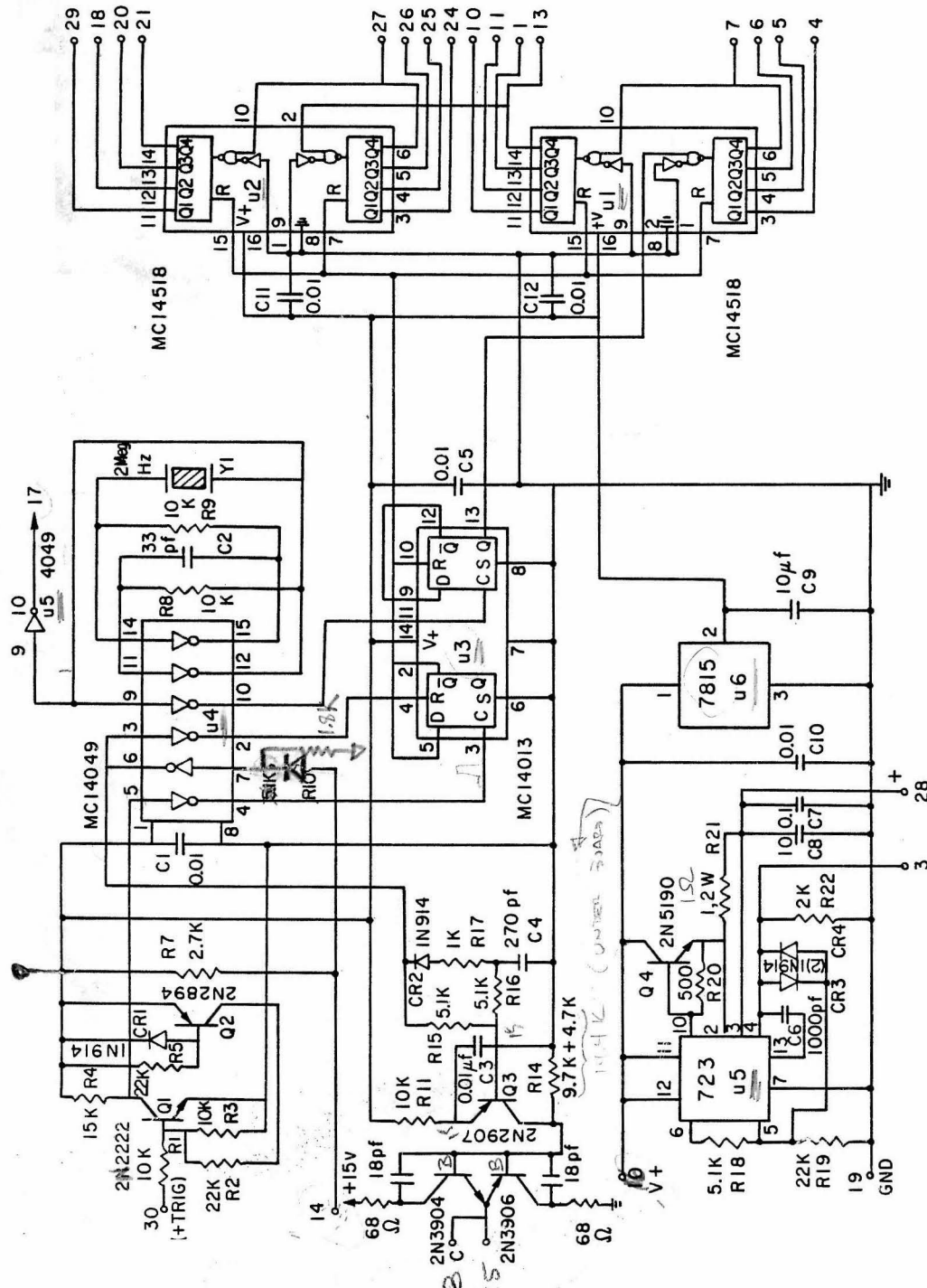
Figure II-6





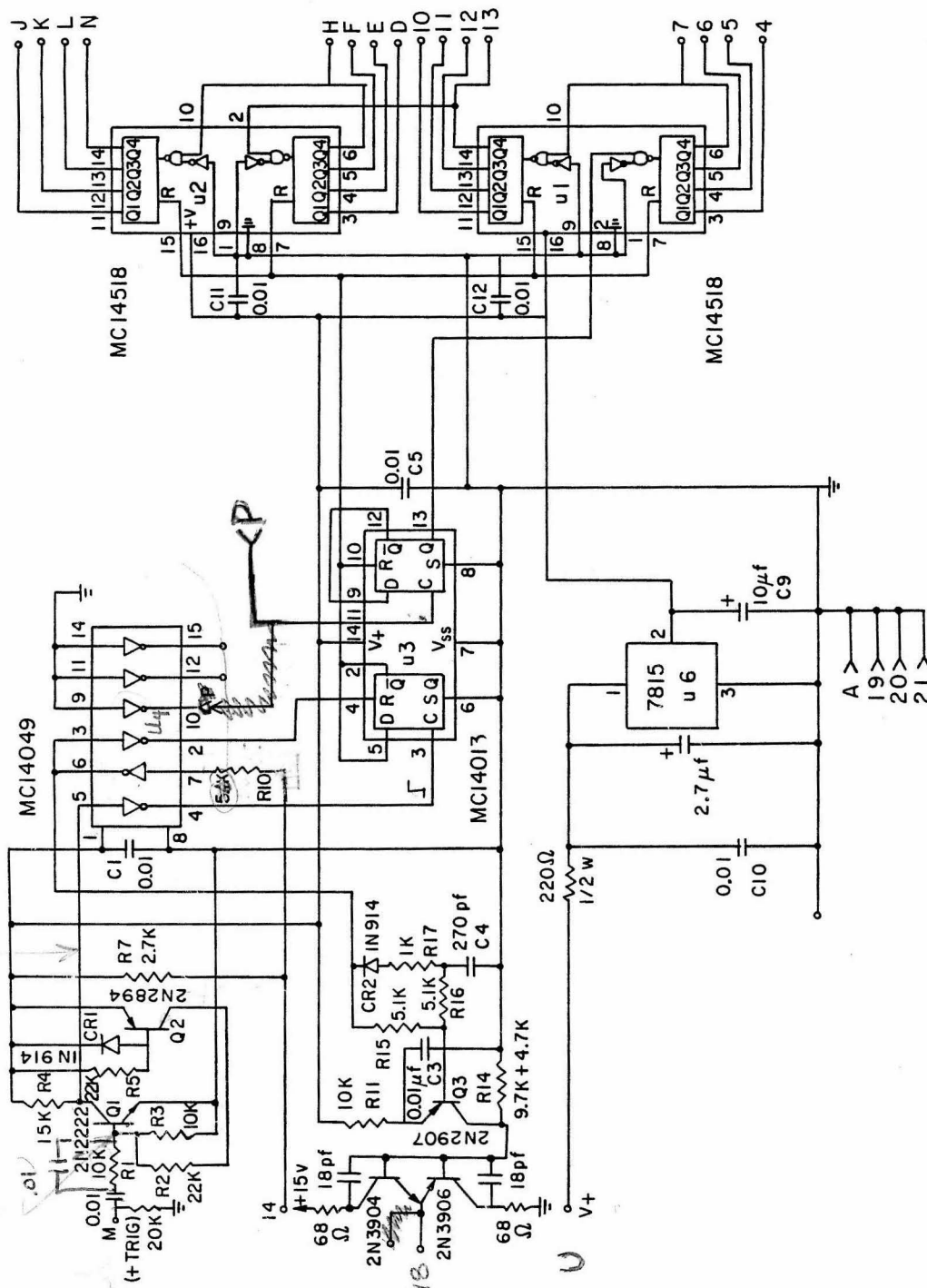
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Figure II-7



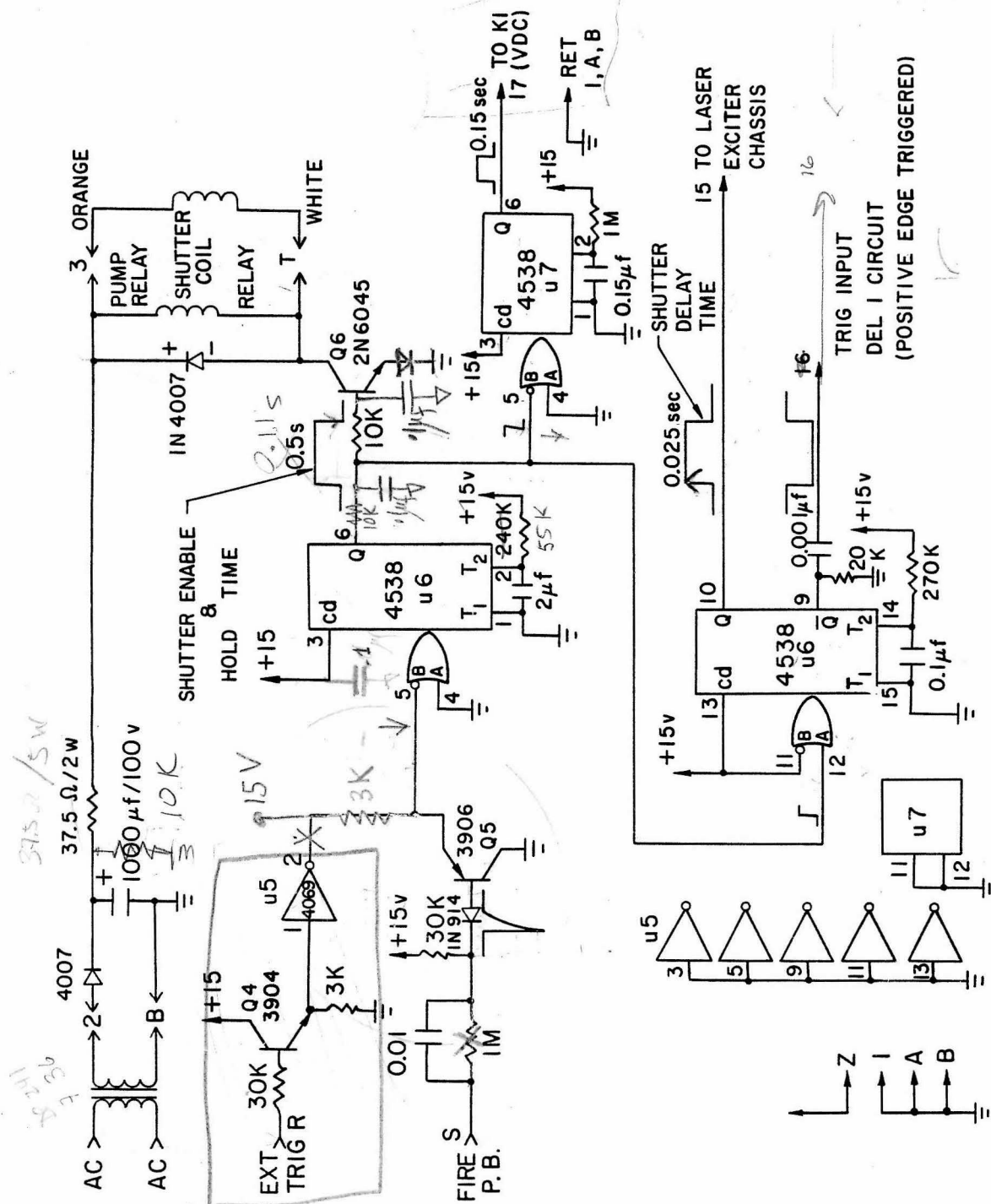
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Figure II-8



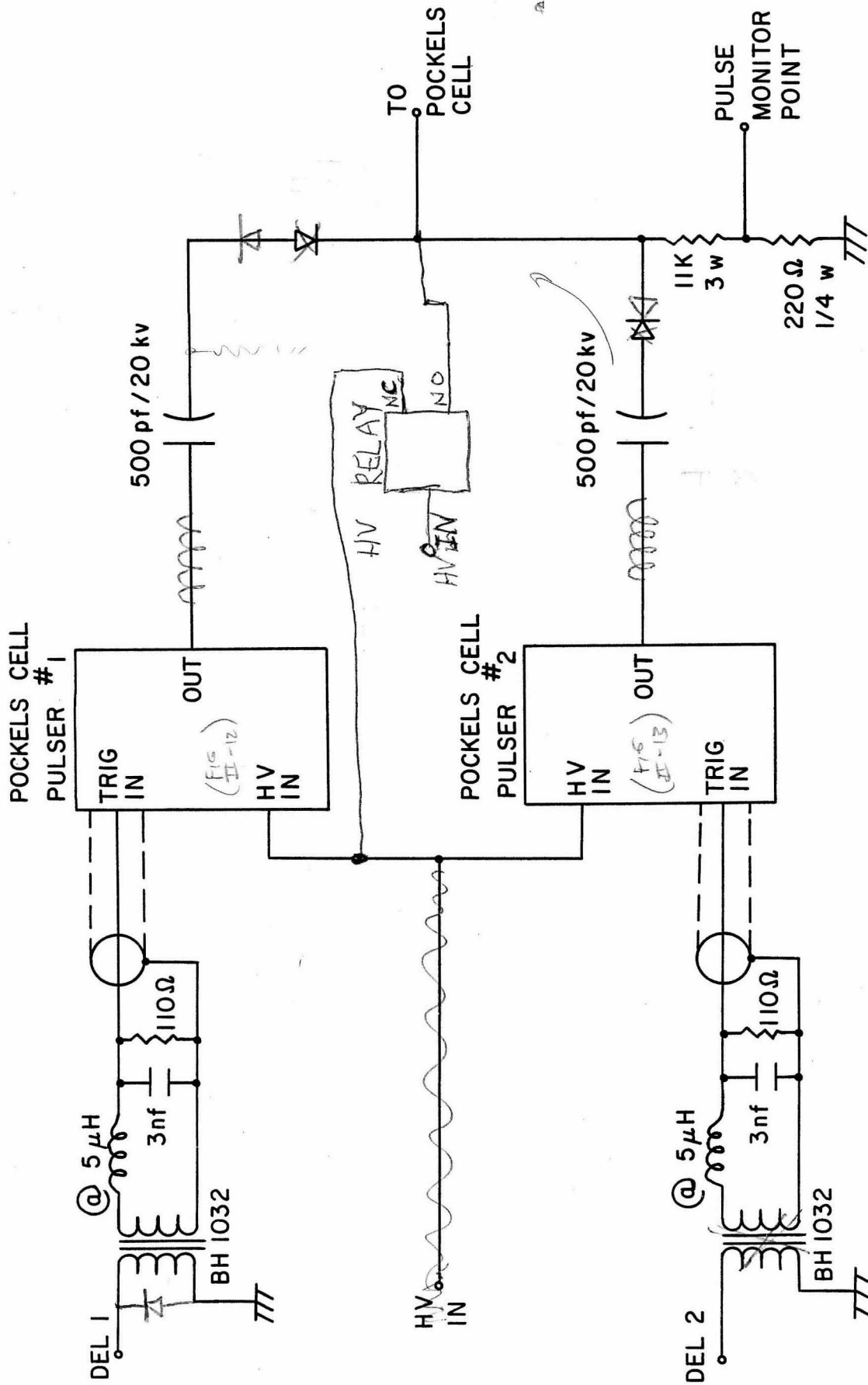
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Figure II-9



## APPENDIX II

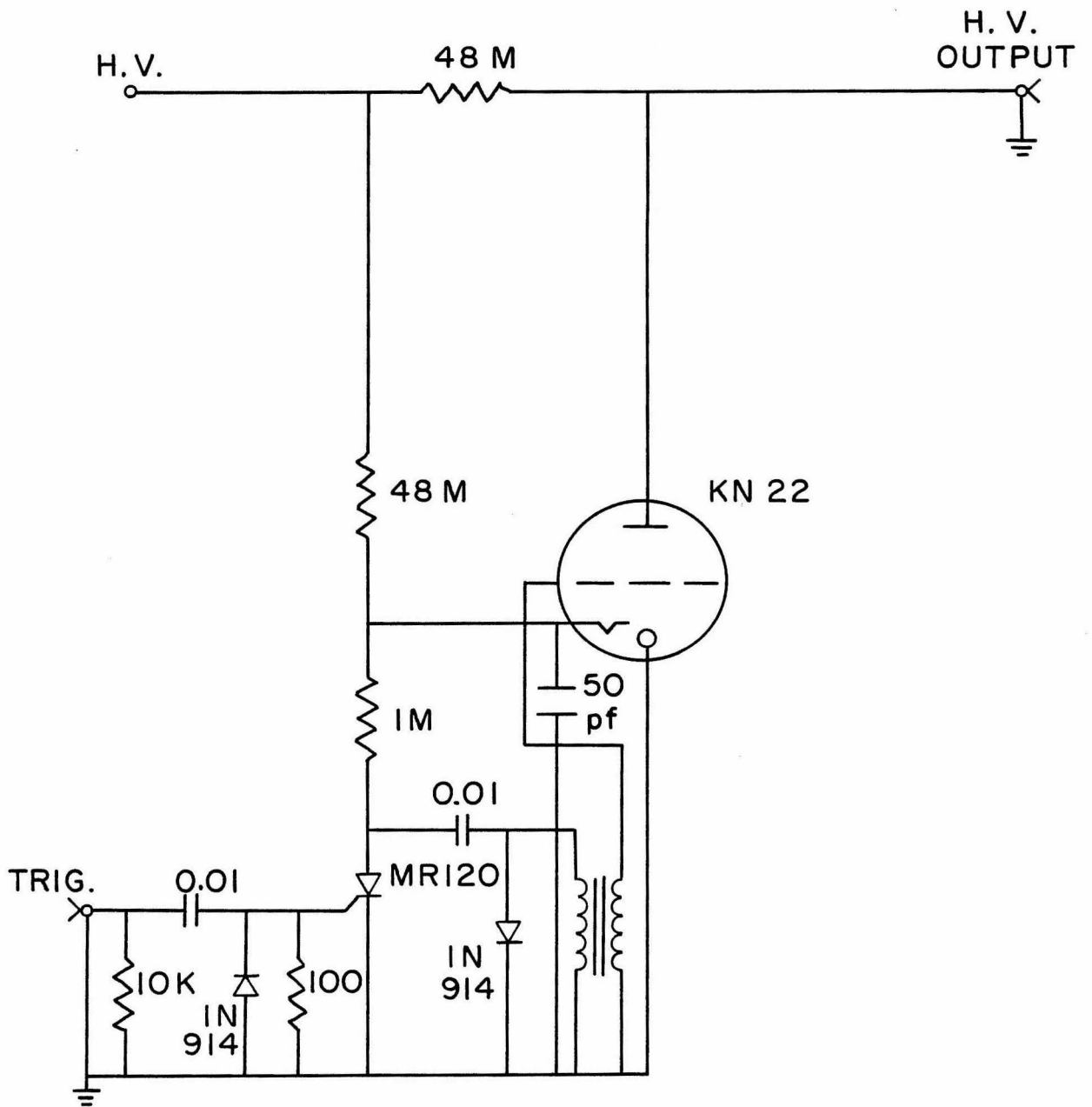
Figure II-10



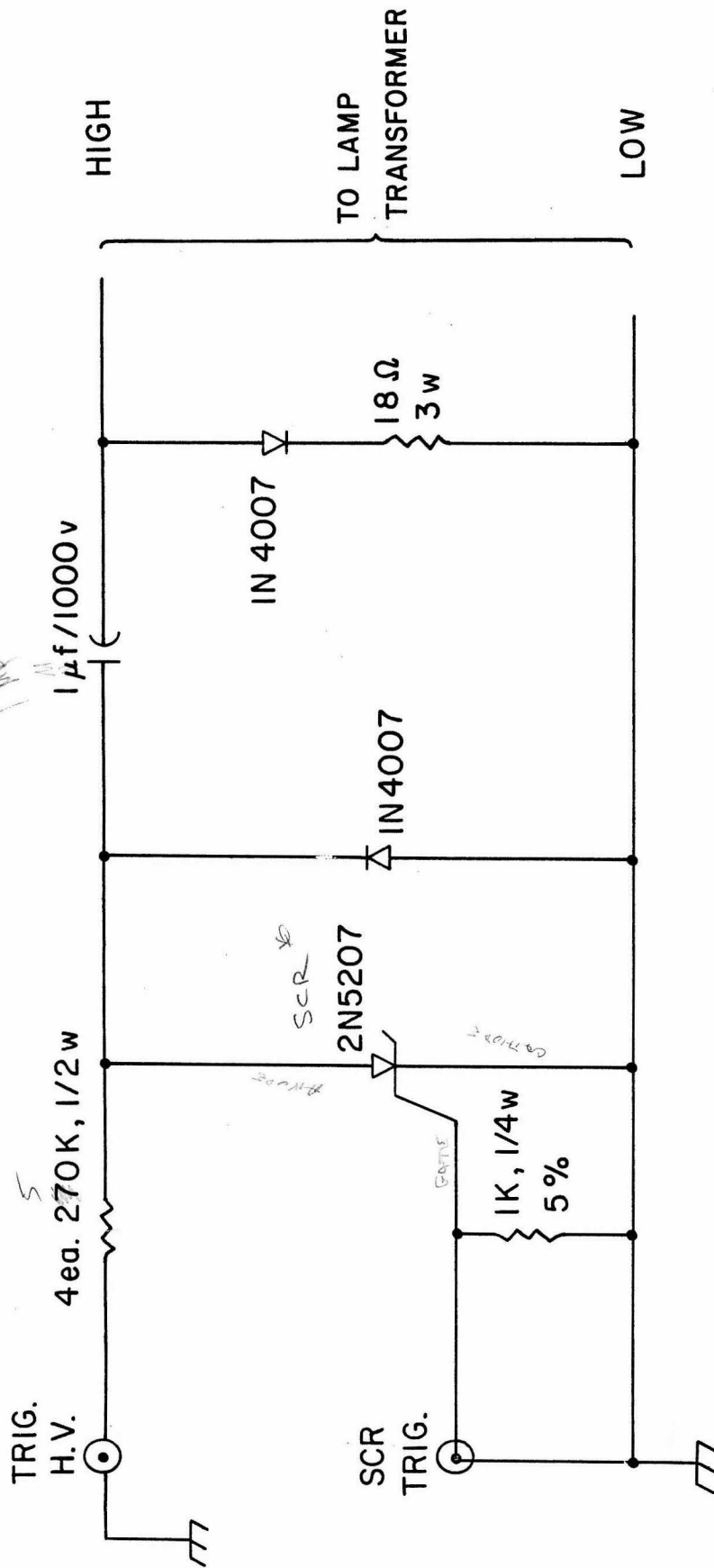
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Figure II-12

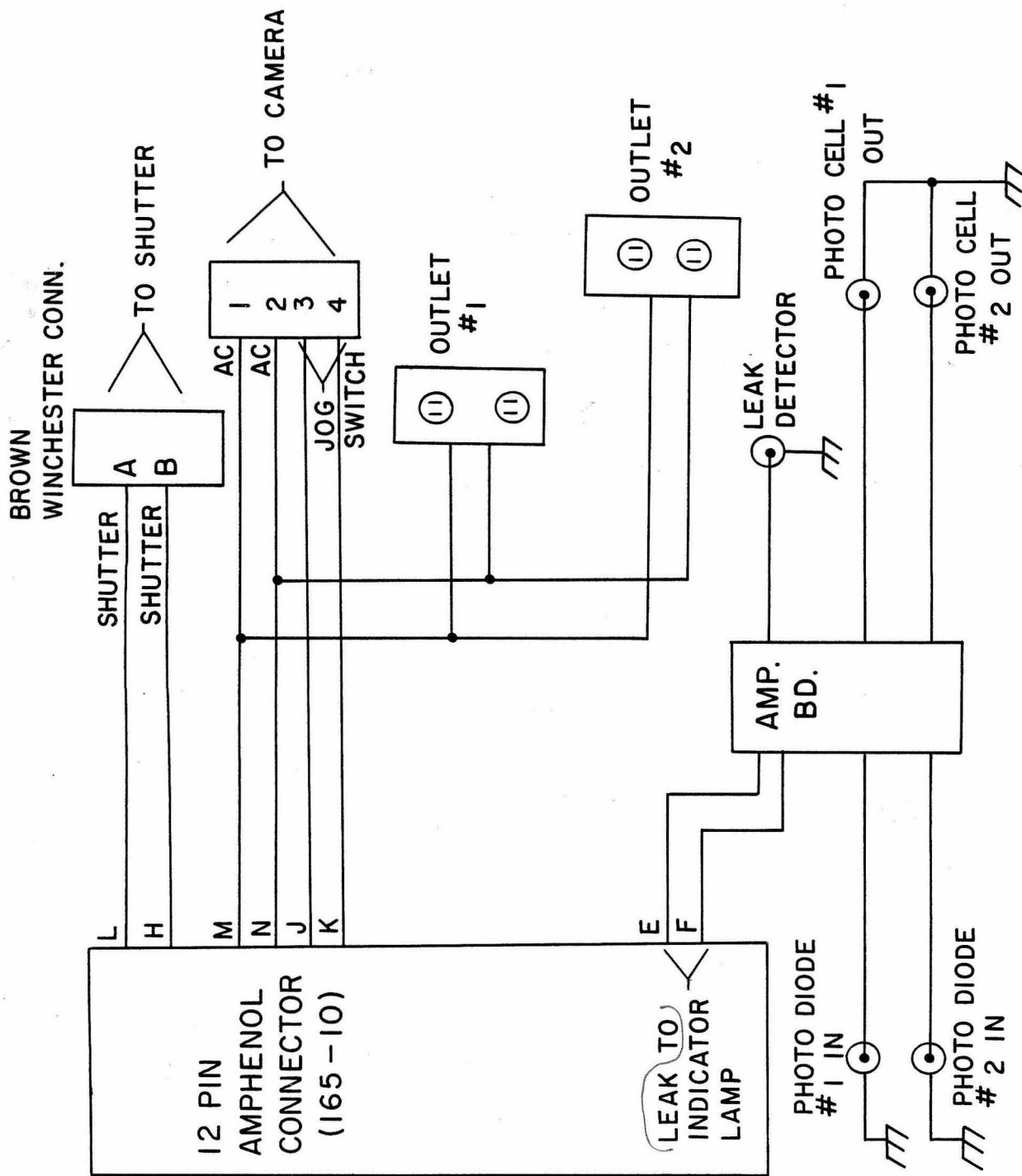


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Figure II-13



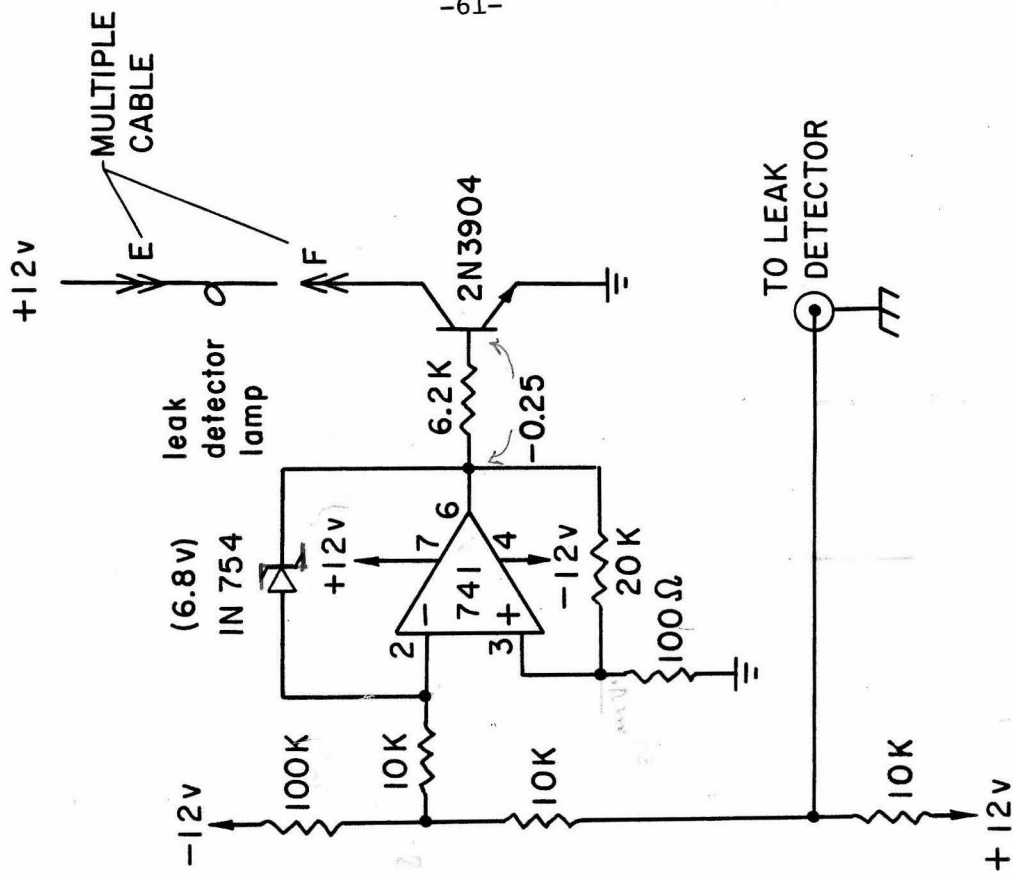
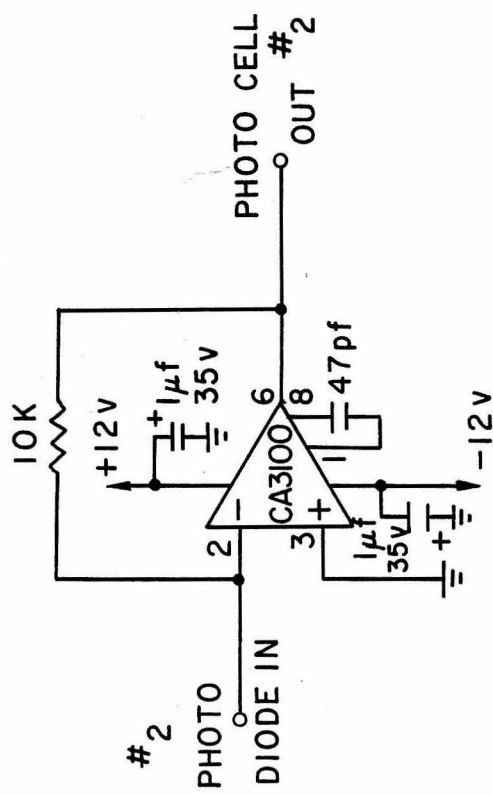
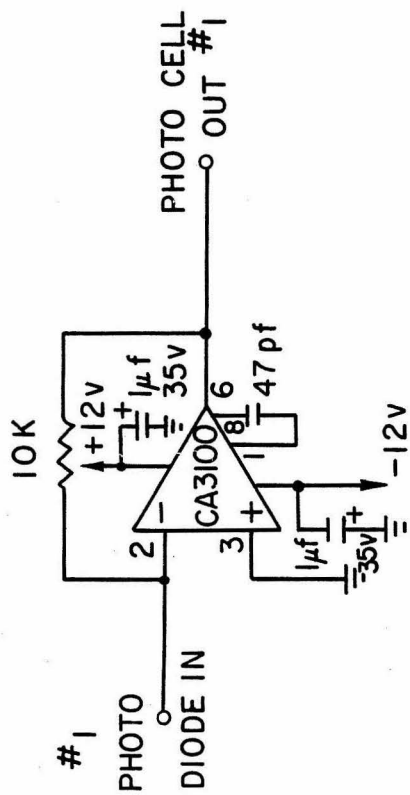
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Figure II-14





APPENDIX II

Figure II-15



### APPENDIX III

#### Deaerator System

This deaeration system was designed, built and installed as a part of the present contract in order to control the dissolved gas content in the Low Turbulence Water Tunnel used in the comparative study of Ref.10. The design itself was accomplished by Dr. K. K. Ooi. A brief description and photographs of the assembly are taken from Ref.13 and are appended here for completeness.

Reference 13:

Ooi, K. K., 1981, "Scale Effects on Cavitation Inception in Submerged Jets", Calif. Inst. of Tech., Report No. 183-6, December.

Chapter 2, Section 2.3

2.3 Deaerator System

Figure 2.2(a) is a schematic diagram of the deaerator system, while Figure 2.2(b) shows a photograph of the deaeration tank. The main component is a closed cylindrical vessel measuring 2.54m (100") in length and 0.91m (3 ft) in diameter. Water is pumped (by the supply pump) to the top of the tank from the water tunnel. The water is then forced through a set of 10 "Bete Spiral Nozzles", Model No.TF28FC, mounted on a horizontal section of the pipe, suspended inside the tank, from the top. These commercially designed nozzles effectively atomize the water. The fine sprays then rain down on a packed bed of "Plastic Super Intalox" tower packings resting on a steel grating stretched across the entire length and width of the tank. This is aimed at increasing the surface area from which gas diffusion can take place. The water flows through the packed bed and collects at the base of the tank where a second pump returns the water back to the tunnel. The deaeration process begins when the pressure inside the vessel is reduced by a vacuum pump.

During deaeration, the tunnel water is continuously circulated through the deaeration vessel. It is desirable to prevent flooding of the packed beds because this will drastically reduce the surface area for gas diffusion. Therefore, there is a need to be able to adjust the water level in the vessel. This is accomplished by throttling the flow on the supply and drain lines to the tank until the desired water level is achieved.

To prevent the drain pump from running dry, the drain pump automatically kicks off when the water level in the tank becomes too low. A check valve in the drain line stops any back flow into the tank. This pump remains shut off even though the supply pump is still operating, until the water level rises to a predetermined level. By the same token, the supply pump shuts off when the water level in the tank becomes too high or overflowing will occur. The supply pump comes on again when the water drops to a safe level. These "ON-OFF" actions of the two pumps are controlled by a 4-level "Gems Level Switch", Model No.LS800, mounted on a side viewing glass, and a set of latched relays. When the water level in the tank is properly adjusted, both pumps will run continuously throughout the deaeration process.

The present deaeration system can circulate 200 gpm. It has been found that at this flow rate, the deaeration time was reduced when the water tunnel was kept at a partial vacuum. Figure 2.3 shows the performance curve of the present system at two different tunnel pressures. It should be pointed out that the lower curve represents the limit of the present system because further reduction of the tunnel pressure would soon cause the supply pump to cavitate. The air content is measured with a Van Slyke Blood Analyzer.

The present deaerator thus allows an easy control of the air content in the tunnel water.

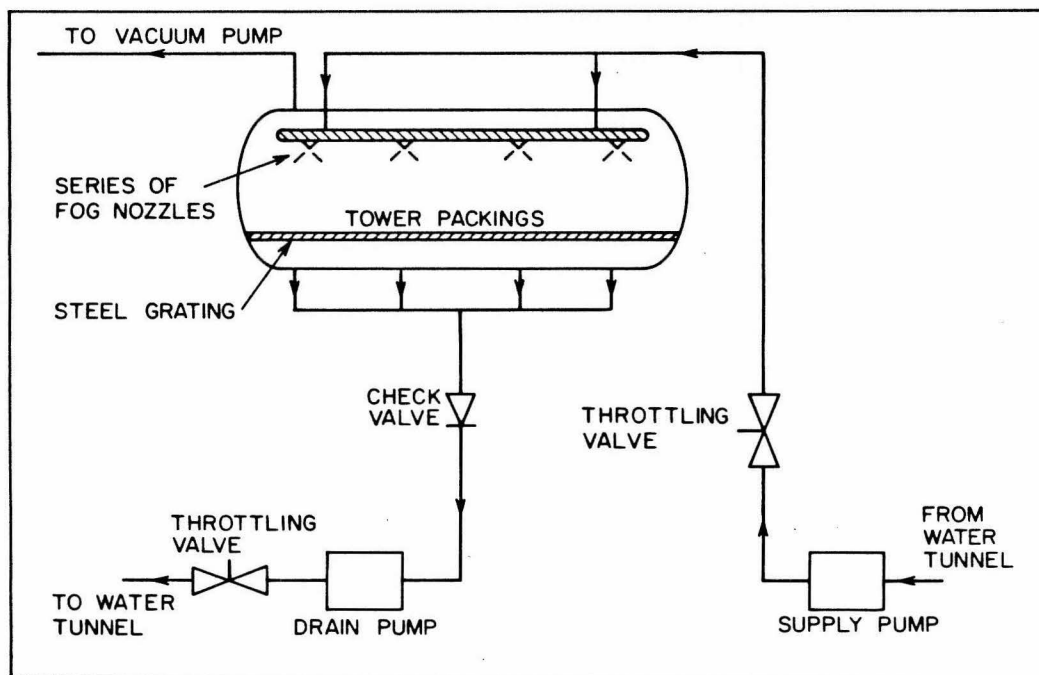


Figure 2.2(a). Schematic diagram of the dearator system.

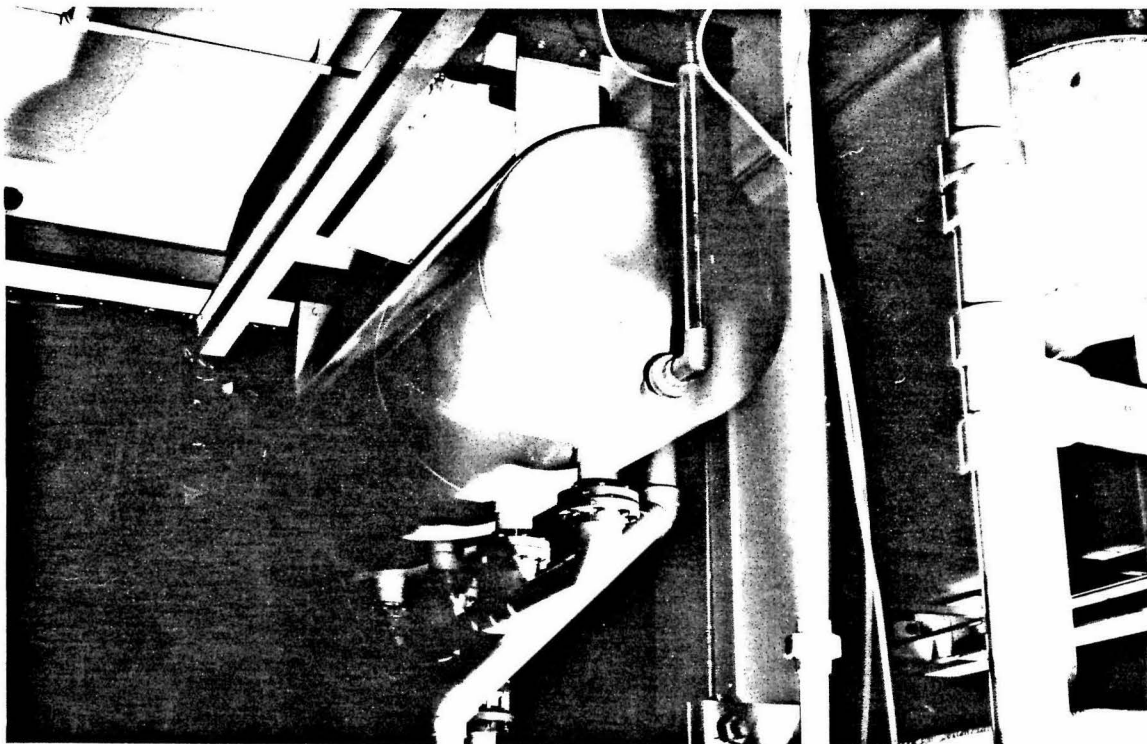


Figure 2.2(b). Photograph of the dearation tank.

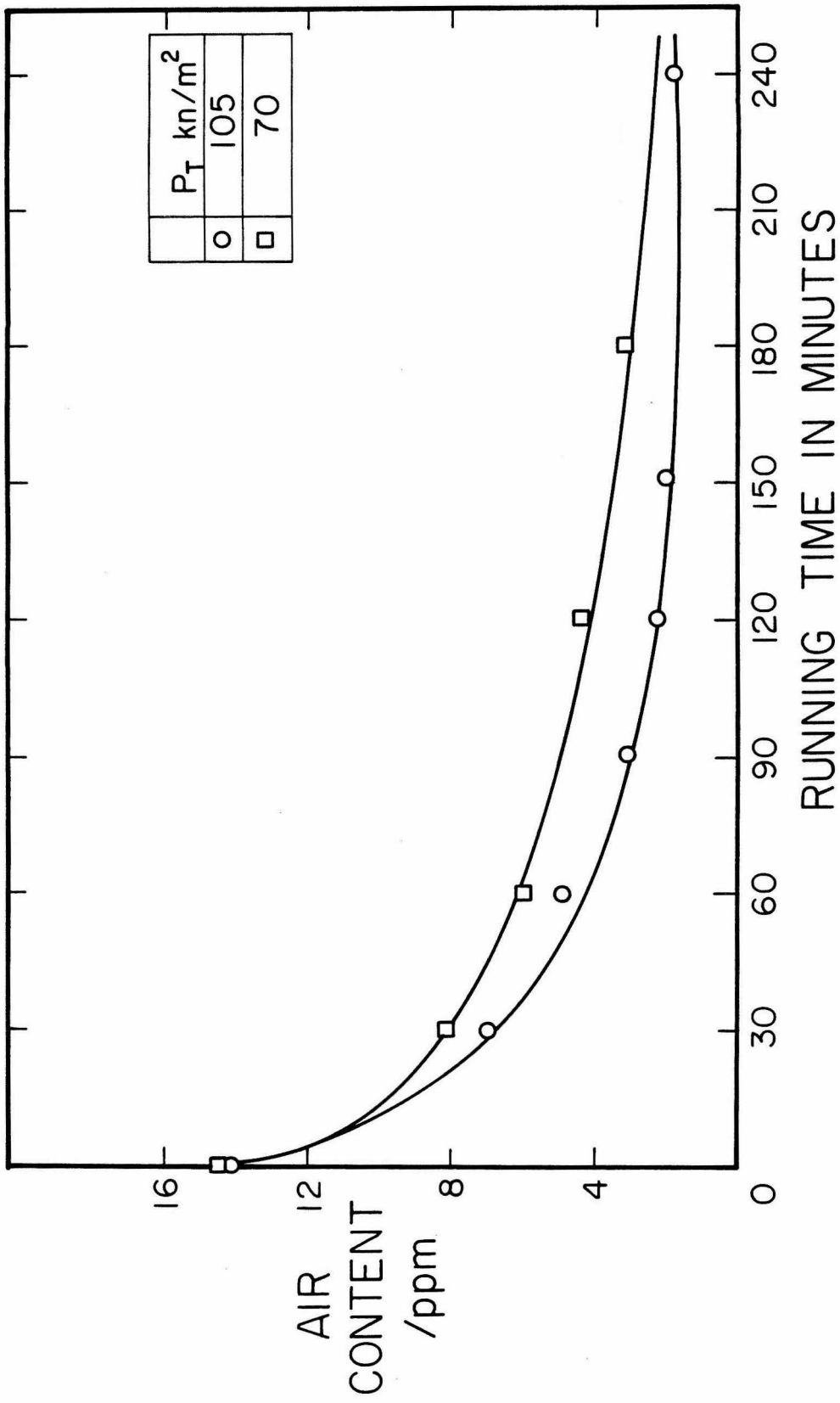


Figure 2.3. Graph displaying the performance curve of the deaeration system.

#### **APPENDIX IV**

##### **Patent Disclosure**



**Invention Disclosure Form**

Date 12/31/82

INVENTOR (S) Joseph Katz

ADDRESS School of Civil Engineering  
Purdue University  
West Lafayette, Indiana 47907

TITLE OF INVENTION Two Dimensional Precision Spatial Filter Holder

DATE OF:

(1) Conception May 17, 1982

(2) First Drawing May 18, 1982

(3) First Written Description December 1982

(4) First Disclosure to Others May 18, 1982

(5) Completion of First Model June 1, 1982

(6) First Test June 2, 1982

NAMES OF WITNESSES:

Elton Daly/A. J. Acosta

Elton Daly/ A. J. Acosta

A. J. Acosta

Elton Daly/Joseph Fontana

Elton Daly/A. J. Acosta

Prof. A. J. Acosta

Brief Description of Invention Two dimensional translating stage for positioning  
pin-hole spatial filters or optical fibers.

Brief Outline of Present State of Development Unit fabricated and installed in working  
holographic camera.

New and Useful Features of Invention Use of two perpendicularly mounted pairs of dovetails  
kinematically arranged to prevent stiction to position and lock floating frame in place.

Do you know of any prior art or claims to prior art? No

Formula or sketch illustrating invention (use additional sheets if necessary):

See attached

RECEIVED

DEC 18 1982

CALTECH  
PATENT OFFICE

List by number all Drawings, Photographs, Reports or Publications known to you which further describe the invention or relate thereto:

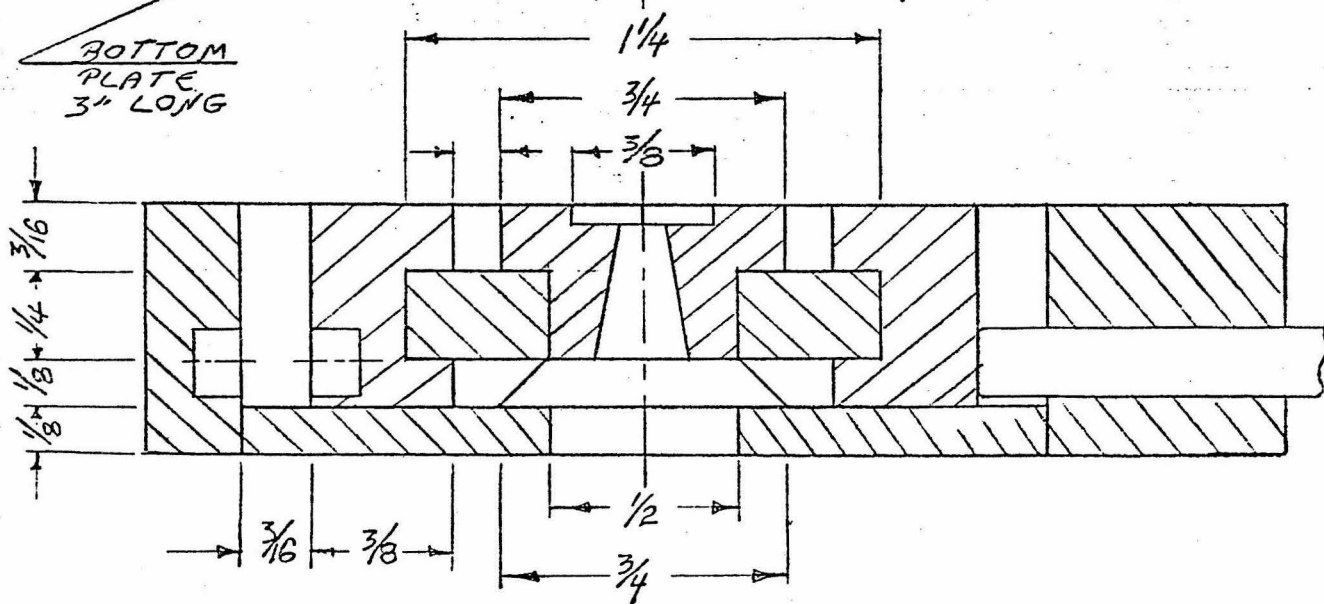
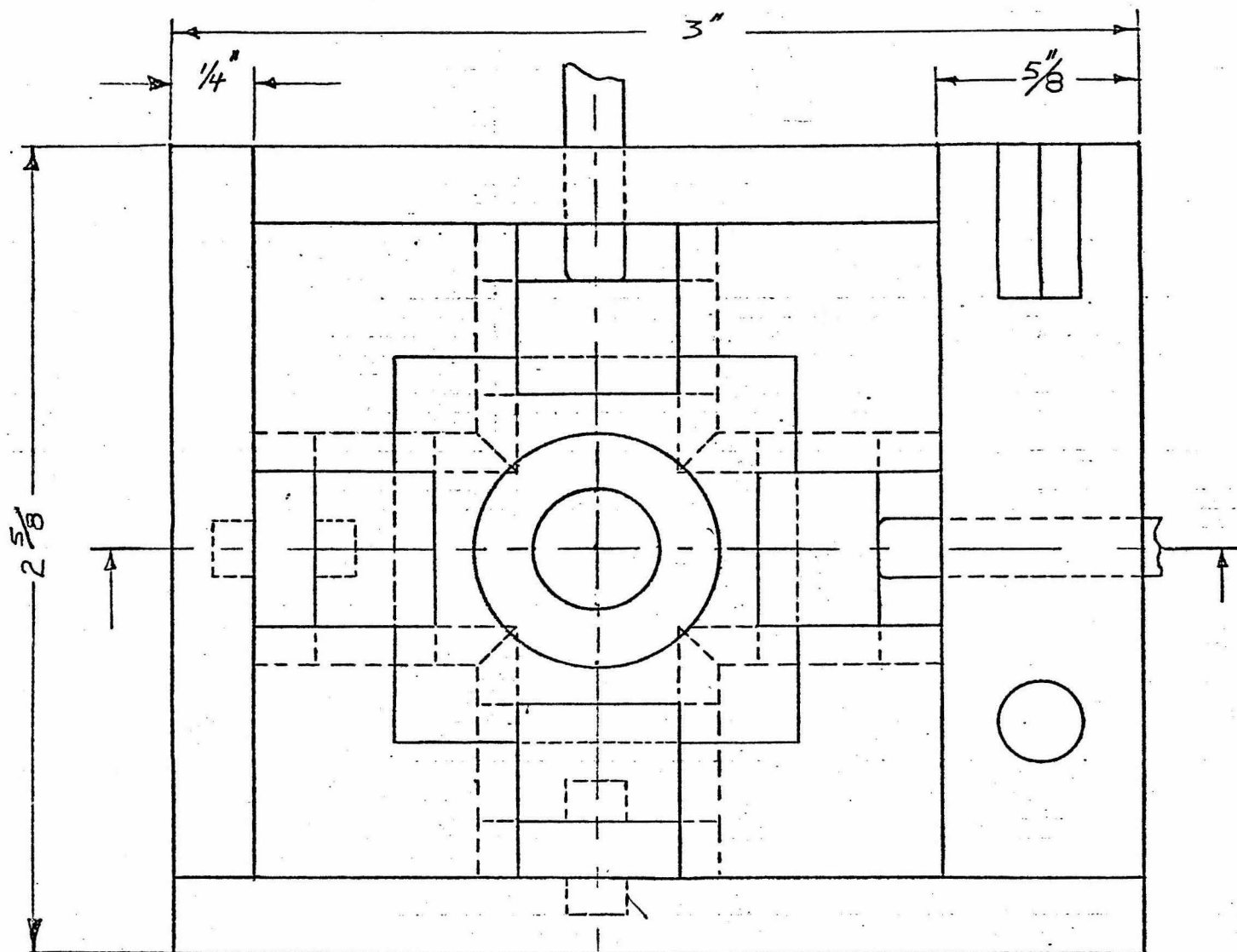
Contracts involved: (Contract Number) N000-14-75-C-0378

SIGNATURE OF WITNESSES TO THIS  
DISCLOSURE:

Elton J. Daly  
Joe Fontana  
Alban J. Acosta

SIGNATURE OF INVENTOR (S)

Joseph Katz



(3)

Joseph Katz

(2)

Joseph Katz

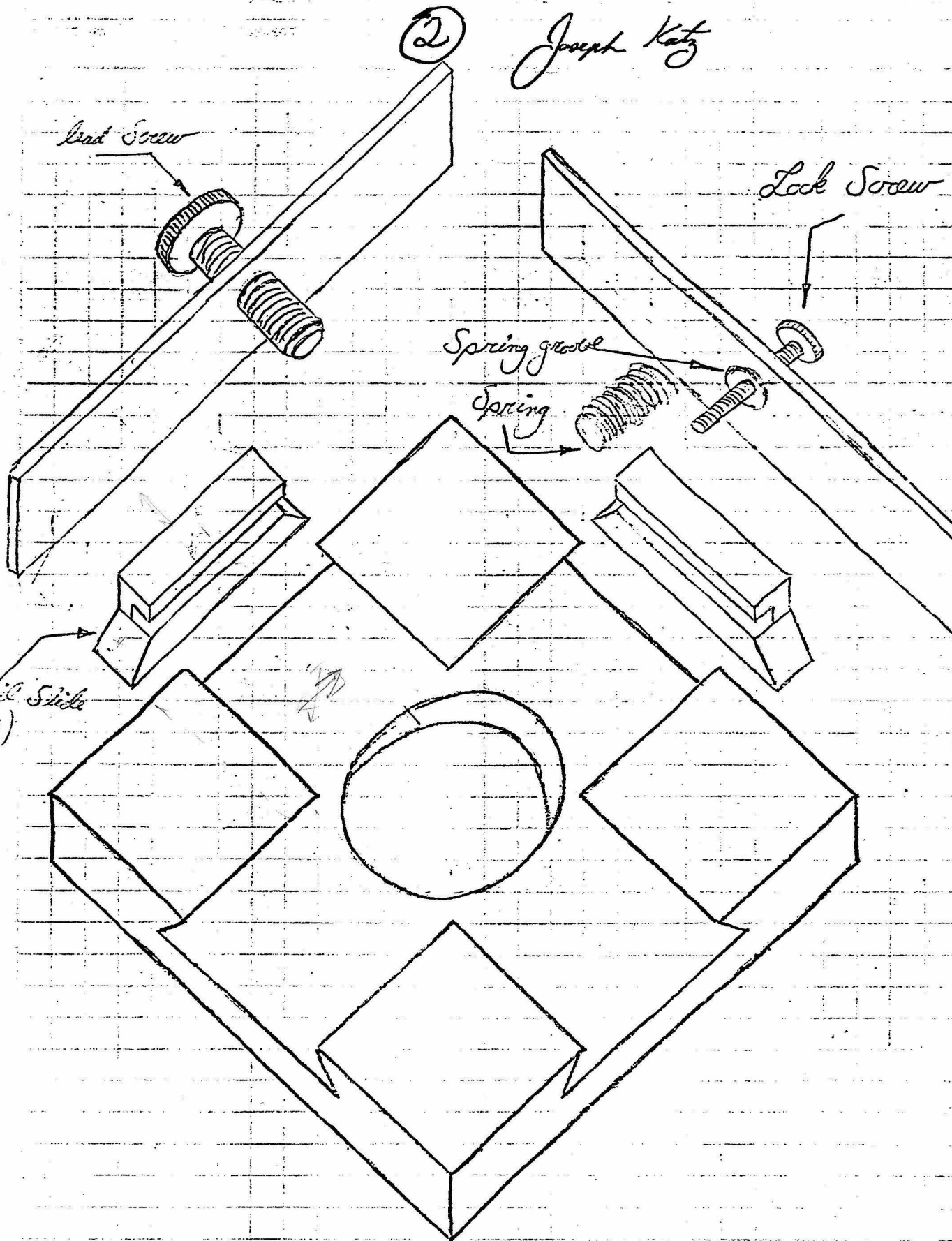
Lead Screw

Lock Screw

Spring groove

Spring

Detail Slide  
(x4)



① Joseph Kety

